Managing Fertilizers to Enhance Soil Health

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EXECUTIVE SUMMARY

Mankind is dependent on the soil for its needs for food and fiber for humans, feed for livestock, and, of late, contributing to our energy supply with crops grown primarily for biofuels. Soil is a dynamic and multifunctional living system that exists as a relatively thin layer on the Earth's crust. The various combinations of soil forming factors have given rise to an exceptional diversity of soil types across the world. The properties of soils and associated environmental conditions govern the various ecosystem functions of soil such as decomposition and transformation of organic wastes, mediating nutrient cycles, and influencing populations of soil organisms such as bacteria and fungi. While it is difficult to describe how well any soil performs its inter-related functions, earlier definitions included 'fertility', and later ones implied 'quality' and more recently 'soil health', a more inclusive term.

Historically, where soils were fertile and capable of producing adequate crop yields, and where there was enough water, either as rainfall or irrigation, civilizations flourished. In the past century, world food production increased dramatically due to enhanced crop yields as a result of widespread adoption of technologies such as mechanization, new high-yielding and disease-resistant crop varieties, irrigation, and especially the use of mineral fertilizers. While crop yields were the primary focus in the past, awareness of increasing population growth and limited potential to bring more land into production led to the notion of cropping sustainability or sustainable intensification, i.e. consistently achieving high crop yields without damaging the soil's capacity to produce such yields. Thus, the current focus in soil and crop management is on maintenance of soil quality or soil health. That raises the issue of how fertilizer use affects the soil other than its effects on crop yields.

While soil health can be affected by limited nutrient input from fertilizers, application of amounts of fertilizer nutrients above the crop's needs for optimum growth can be equally detrimental to soils and reduce economic profitability. Low or unbalanced fertilization leads to depletion of soil nutrients and degradation due to lower soil organic matter (SOM) contents from lower root biomass associated with reduced crop yields, and indirectly reduced soil structure which promotes soil erosion. Conversely, regular adequate fertilizer use is associated with small but consistent increases in SOM as a result of increased root biomass, despite the popular misconception that N use leads to decreased SOM. While fertilizer use has been associated with reduction in some soil organisms, these effects are relatively short-lived and only at the site of the fertilizer band. Significant increases in microbial biomass have been shown by long-term application of fertilizers in non-acid soils. Transformation of ammonium-based N fertilizers in soils can adversely affect soil health by increasing acidity. The extent, to which this natural microbial-mediated process can impact the soil, and thus crop growth, is dependent on the form and amount of N applied and the soil's

buffering capacity. Maintenance and/or improvement in soil health in terms of SOM content and supply of various micronutrients is possible when farmers apply organic nutrient sources such as manures and crop residues available on the farm and supplement them with mineral fertilizers to achieve the yield goal.

In summary, mineral fertilizer use is essential to modern agriculture and ensuring food security for mankind. In addition to enhancing crop yields, fertilizers can indirectly affect soil properties or soil health, either positively or negatively. The key to ensuring positive effects on soil lies in good science-based nutrient management practices; adoption of such practices ensures that economic crop production is compatible with minimizing environmental effects. Wherever possible, available organic manures and other organic materials should be used in an integrated fashion with mineral fertilizers to ensure efficient and effective nutrient use as well as better soil health.

INTRODUCTION

As a prelude to considering soil health in relation to fertilizers, it is pertinent to present some well-established facts that provide an overall context to the discussion. The main body of the article considers the importance of soils, the concept of soil health, and the positive and negative effects of fertilizers on soil health, with a focus on indirect effects on soil acidity, soil erosion, soil microbial populations, fertilizers in relation to SOM maintenance, and integrated nutrient use, followed by perceived research needs in relation to soil health.

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SOIL – A BASIC BUILDING BLOCK FOR LIFE ON EARTH

In recent years, much has been written about soil quality in relation to food security (Lal and Stewart, 2010) because of a renewed awareness of the relationship between human population and the Earth's capacity to produce enough food to sustain the world's burgeoning population. In the context of this brief discussion of fertilizers and soil health, it is pertinent to put the global situation with respect to food in perspective. The food balance sheets prepared by the United Nations Food and Agricultural Organization (FAO) show that more than 99.7% of human food (calories) comes from the terrestrial environment, i.e., agricultural land (Pimentel and Wilson, 2004). Of the 13 billion ha of land area on Earth, cropland accounts for only 11%. About 78% of the average per capita calorie consumption or energy needs worldwide comes from crops grown directly in soil, and another more than 20% comes from other terrestrial food sources such as meat, eggs and milk that rely indirectly on soil (Brevik 2013). Soil is fundamental to crop production and thus constitutes the natural resource that provides mankind the most of its food and nutrients.

SOIL, FERTILIZER AND CROP-RELATED GENERALIZATIONS

- Soil types vary widely throughout the world, depending on location (geology, climate, vegetation) with corresponding variation in the combination of physical, chemical and biological properties that support agricultural crops.
- Soil fertility, or the soil's reserve of crop nutrients, is broadly equated with soil quality and soil health. A fertile soil is a productive soil if growing conditions are favorable, e.g. adequate soil moisture and aeration, and neither too hot or too cold for crop growth.
- As soils vary in fertility, few can sustain high crop yields indefinitely without application of nutrients. For economic yields required in today's agriculture, nutrients have to be added to the soil as mineral fertilizers and/or organic manures. Prior to the modern era of commercial agriculture, modest yields were achievable by adding organic manures, adopting crop rotations with legumes, or resting the land, i.e. fallow.
- In the past half century, expansion in global crop output, and thus food security, was achieved largely by using mineral fertilizers -- along with improved crop varieties, mechanization, pest and disease control and irrigation. Globally, cereal yields have paralleled fertilizer use. Today, about half of the world's crop output is attributed to fertilizers.
- All crops remove nutrients from the soil. Where removal exceeds inputs, nutrient depletion or nutrient "mining" occurs--a condition that is not sustainable. An example of this imbalance is found in many African countries. Soil degradation is associated with low yields and human poverty.
- Fertilization practices need to be "balanced". The amounts of major nutrients added in fertilizers must be based on what is already in the soil and what is removed in the crops.
- Fertilizer use efficiency implies the extent to which added nutrients are taken up by the target crop. In the case of N, efficiency is rarely above 50%, leading to losses from the field and potential negative impacts on the environment; current research is aimed at improving efficiency. Fertilizer use efficiency can be improved by adopting fertilizer best management practices.
- Contrary to popular notions, the use of mineral fertilizers can enhance soil health, through increasing SOM as a result of the greater root growth associated with improved crop yields; this is often accompanied by enhanced microbial activity. The extent to which this occurs depends on the environment and associated tillage practices.
- Fertilizer use can result in reduction in some soil organisms, but these effects are relatively short-lived and occur only at the site of the fertilizer application band. Significant increases in microbial biomass are observed by long-term application of fertilizers in alkaline or neutral soils.
- Application of ammonium-based N fertilizers can adversely affect soil health by inducing soil acidity. However, the effect is dependent on the form and amount of fertilizer N applied, the soil's buffering capacity, and soil pH management practices such as liming.
- In terms of effects on soil health, crop production or the environment, there is no conflict between mineral fertilizers and organic nutrient sources; quite the contrary, their use is complimentary.
- Soil health improvement in terms of SOM content is possible when nutrients contained in different organic materials available on the farm (manures, crop residues, etc.) are applied and supplemented with mineral fertilizers to meet the nutrient requirements of the crops.
- Mineral fertilizers are indispensable to ensuring food security for the world's population of over 7 billion people. That dependence will be even greater in the future as the population increases and with increased affluence in some countries.
- Fertilizer use is also likely to increase with expansion of farming to less fertile areas as a result of competing demand for land use, as well as negative consequences of climate change.
- The sustainable use of fertilizers for mankind will have to be based on sound scientific principles and practices.
- Benefits of using fertilizers will have to be better communicated to the public at large.

Because soil is finite and fragile, it is a precious resource that requires special care and conservation so that it can be used indefinitely by future generations. The crucial role of soils in supporting human existence on the planet Earth can be judged from the facts that it takes about 500 years or more for 2.5 cm of topsoil, depending on the weathering environment, to become usable under agricultural conditions; in short, soil formation is a very slow process. With a growing world population and limited possibilities for expansion of cultivated land area, per capita calorie production has consistently decreased in the past decades. For example, the quantity of cereal grains produced per capita has been declining since 1984. The extent of this general trend varies between countries depending on development status, relative population growth, and food diversification. In addition, following decades of significant productivity increases, relative yield gains are declining. One of mankind's greatest challenges is to increase productivity and move off the yield plateau.

This leads to a consideration of soil and its properties. Well-known and established facts about soil can be found in many standard textbooks such as that by Brady and Weil (2010) and other widely used sources. To the lay person, soil is mainly a medium for growing crops; many people just consider it "dirt". To the soil scientist or agriculturalist, it is a far more complex material.

Soil is the relatively thin mantle on the Earth's surface that varies in depth from a few centimetres to several metres in extreme cases; the normal soil depth is up to one metre. Soil is distinguished from weathered rock that lies beneath it mainly by its biological functions, which operate by complex interactions with the abiotic, physical, and chemical environment. In other words, soil is a product of biological transformations. Soil is a living system and is habitat for many different organisms that collectively contribute to different functions of the soil. The realm of soil microbiology is as yet poorly explored, and majority of the various species that inhabit the soil are not yet identified.

The major beneficial functions of soil for providing sustenance to mankind are driven by soil biological processes that can be aggregated into four ecosystem functions (Kibblewhite *et al.*, 2008):

(i) Carbon (C) is central to all soil organisms, as it is their energy source, and in turn gets changed into different forms. Carbon transformations by soil organisms involve decomposition of plant residues, various forms of organic matter resident in the soil, and other organic materials. These processes regulate nutrient cycling and waste disposal, and SOM synthesis, including activities of the soil biota for maintenance of soil structure as well as emission of greenhouse gases.

(ii) Nutrient cycles involving different complex pathways or transformations both in the ground and aboveground define availability of various nutrients to plants.

(iii) Maintenance of the structure and fabric of the soil by aggregation and particle transport, and formation of bio-structures and pore networks across many spatial scales is essential for the soil habitat, as well as the regulation of the soil-water cycle and sustaining a favourable rooting medium for plants.

(iv) Biological regulation of soil populations underpins biodiversity conservation and controls pests and diseases of agriculturally important plants and animals, as well as humans.

Soil is a very complex multi-component and multi-functional system with definable operating limits and a characteristic spatial configuration. Dominant physical and chemical properties of a soil are associated with recognizable soil types that originate depending on variations in factors, such as parent material, climate, and thus vegetation, topography, and time, which reflects the extent and intensity of weathering. A major factor in influencing soil properties is man, especially since the advent of settled agriculture and cultivation of the soil.

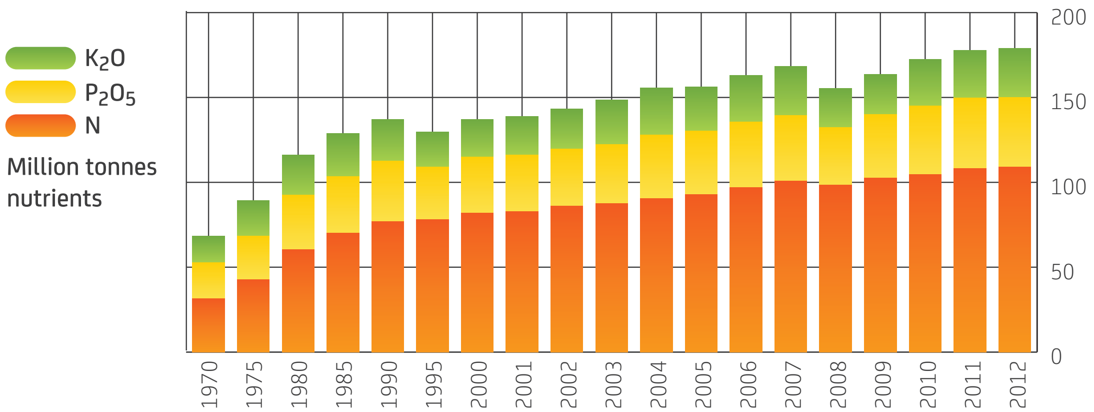
Soil properties, especially in the top layer (to about 30-50 cm) are invariably altered by agricultural interventions, such as drainage, irrigation, use of lime and additions of plant nutrients through mineral fertilizers and organic manures, and particularly by tillage practices; in the USA in the 20th century, conventional diesel-fuelled ploughing and harrowing was seen as the cause of dramatic decreases in SOM, but this situation is now changing with conservation tillage practices. Except in remote and uninhabited parts of the world, it is rare to find any soil that is not affected by man and which is still in its pristine state.

The main driver for anthropogenic interventions over the past century is the quadrupling of world population, which demanded a fundamental change in soil and crop management in order to produce more food (Lal and Stewart, 2010). To feed and clothe the world's burgeoning population, more land had to be brought into cultivation and greater productivity was required from land already in cultivation. The widespread use of commercial mineral fertilizers has been the major factor in ensuring global food security so far. It is pertinent in this context to examine some of the global fertilizer use trends and projections. Total world fertilizer consumption reached 178.9 million metric tonnes (Mt) of nutrients in 2012, of which nitrogen (N), phosphorus (P) as P_2O_5, and potassium (K) as K_2O were 109.1, 41.1 and 28.7 Mt, respectively (Figure 1). Out of this total, slightly over half (50.8%) have been applied to cereals (Heffer, 2013). Availability and application of N fertilizers has been the most important determinant of yield in all major crops. The UN's mid-range forecast is that the current 7.2 billion people will grow to 9.6 billion by 2050 (Glenn *et al.,* 2014). According to projections of the World Resources Institute, the world faces a 69% gap between crop calories produced in 2006 and those most likely required in 2050. As per FAO's revised projection on world agriculture, global agricultural production in 2050 should be 60% higher than that of 2005/2007 (Alexandratos and Bruinsma, 2012). 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 (Searchinger *et al.*, 2013). Increased food production will require intensified production due to the fact that the amount of available arable land is finite.

Over 48% of the more than 7 billion people alive today are living because of increased crop production made possible by applying N fertilizers produced using the chemical engineering feat of the Haber-Bosch process developed in the early 1900s (Erisman *et al.*, 2008); this is one of the milestones in the history of humanity. Meeting the world's escalating food needs and averting widespread starvation cannot be achieved without fertilizer inputs. At least 50% of crop yield is attributable to commercial fertilizer nutrient inputs according to data generated from several long-term studies in the USA, England, and the tropics (Stewart *et al.*, 2005). The extent to which world food production depends on fertilizer use will inevitably increase in future. Without fertilizers, the world would produce only about half as much staple food, and more forested lands would have to be put into production (Roberts, 2009). Current estimates of food needs in the future and the dependence on fertilizers are likely to be underestimated if we consider increased affluence in countries such as India and China and the related increased demand for meat. As nutrients supplied

FIGURE 1

Global consumption of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) supplied through fertilizers (data source: IFA, 2015).



by mineral fertilizers play a critical role in the world's food security and are important from both the yield and food quality perspectives, the challenge ahead is to wean agriculture away from current unsustainable practices and to manage fertilizers and soil in a sustainable way so that not only food demands are continuously met, but soil remains healthy to support adequate food production with minimal environmental impact in the future.

SOIL HEALTH AND FERTILIZER USE

The major function of soil is to provide enough food and ensure human health. Increasingly, there is an awareness of the direct link between soils and human health in terms of elements that enhance health such as N, P and zinc (Zn), and other elements such as cadmium (Cd) and arsenic (As) that are harmful to human health (Brevik and Burgess, 2013). The concept of "health" also applies to the soil, and that is something that we as humans can influence. Soil supports a huge diversity of life in the form of a dynamic ecosystem. Therefore, when the system is viewed as a whole, the concept of soil health, like that of human health, is not difficult to understand.

Soil quality (health) is defined as the capacity of a soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin, 1994). In essence, soil health and soil quality are synonymous terms. While the underlying idea is to manage soil in such a way that it continues to perform different required functions without degradation of the soil itself or negatively affecting the environment, there are definite complexities that make the idea of soil health difficult to grasp. According to Kibblewhite *et al.* (2008), a healthy agricultural soil is one that is capable of supporting the production of food and fibre to a level, and with a quality, sufficient to meet human requirements, and to continue to sustain those functions that are essential to maintain the quality of life for humans and the conservation of biodiversity. Soil health is an integrative property that reflects the capacity of soil to respond to agricultural intervention. Intrinsic in this concept is maintenance of soil quality and avoidance of processes such as erosion and nutrient mining that degrade the soil.

In the process of growing crops, human interventions have altered all agricultural soils from their natural state (Lal, 2007). Earliest cultivation was achieved by essentially scratching the surface of the soil by hand implements in order to achieve a seedbed. Disturbance increased further with animal traction, and more drastically in the modern era by heavy machinery. In dry areas, irrigation represented another major external influence on soil. Every human intervention invariably represents major, and sometimes irrevocable, change in the nature and properties of the original soil. During the transition from native to cultivated land, the key issue is to minimize the negative effects of such changes. Indeed, the history of agriculture is replete with examples where civilizations waned or disappeared because of failure to minimize the impact of man on the soil resource.

In the quest for enhancing yield and quality of food and fibre, agricultural management processes such as tillage and application of fertilizers are the major factors that influence agricultural soils and their properties. These practices and inputs supplement or substitute for biological functions that are considered inadequate or inefficient for achieving the required levels of production. It disturbs the natural functioning and may affect the output of other ecosystem services. For example, nutrient leakage from the soil–plant system may lead to degradation of surface waters and groundwater and pollute drinking water supplies. Similarly, fine seed-bed preparation may increase the risk of soil erosion and sediment transfer to streams, or lead to rapid surface water runoff and increased flood risk. Thus, an essential component of sustainable agriculture, as embedded in the definition of soil health, is to balance the ecosystem functions in such a way that target of agricultural production is achieved without compromising other ecosystem functions with respect to both present and future needs.

The major impact of inorganic fertilizers on the soil health system and ecosystem functions relates to their effect on primary productivity. Even when fertilizers are applied in somewhat excessive quantities, the effect is on process rates rather than any direct toxic effects. Despite it being a relatively small component of soil in terms of volume, the single most important soil property relating to soil health is SOM because it exerts profound influence on the soil's chemical, physical, and biological properties. Following their introduction, the effectiveness of fertilizers for crop yields was immediately apparent. Initially, the most important indirect consequence of using inorganic fertilizers was a corresponding reduction in the relative amount of organic manure used. Factors that militated against animal manures included limited supplies and energy costs associated with use of manures in cropping systems, e.g., transport and application, in addition to variable quality and low nutrient contents. Subsequently, there was an increased interest in manures due to increasing supplies, and their perceived role in soil health as well as nutrient recycling. However, in several developing countries, particularly in Asia, crop production is relying more on fertilizers because of limited availability of animal manures and crop residues. Grazing practices, often in communal grazing, remove crop residues from the field; in some cases, such residues are burned to make way for the next crop. In South Asia, where about a sixth of the total global fertilizer production is consumed, a significant proportion of animal excreta are used as household fuel rather than as manure for crops.

Soil health is also influenced by increased rate of decomposition of 'low quality' or high C:N ratio organic inputs and SOM when fertilizers are applied to the soil (Recous *et al.*, 1995). Fertilizer application leads to enhancement of microbial decomposer activity, which has been previously limited by low nutrient concentrations in the organic materials, although in a few studies added inorganic N has had either a neutral or even an inhibitory effect on the decomposition of low-N plant materials (Hobbie, 2005). Long-term use of fertilizers in crop production, however, leads to SOM accumulation (Ladha *et al.*, 2011; Geiseller and Scow, 2014) and soil health improvement through addition of increasing amount of litter and root biomass to the soil. It suggests that the application of N fertilizer can have complex interactive effects on C transformations in the soil.

EXCESS FERTILIZER USE: POTENTIAL SOIL HEALTH DETERIORATION

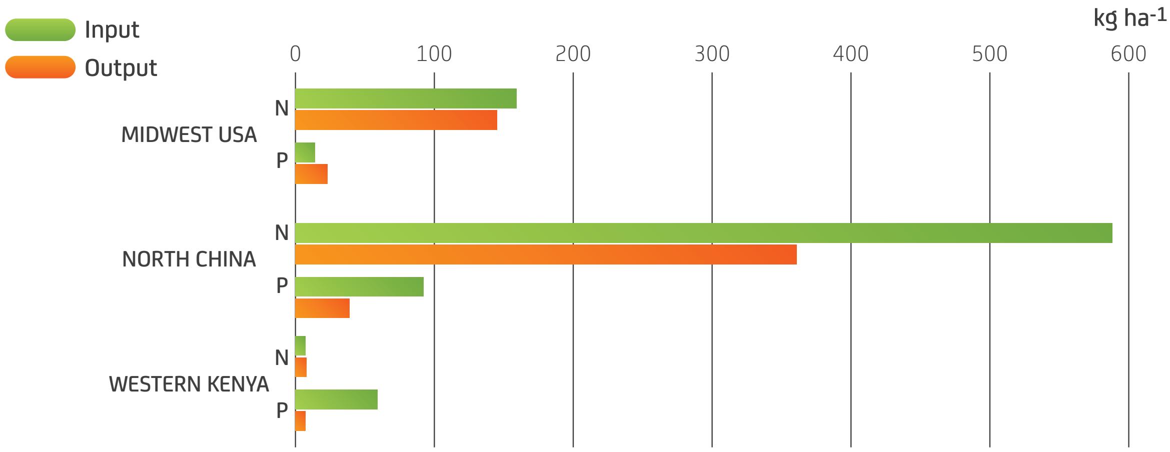
A sustainable soil health management system, which has the capacity to produce higher yields while using fewer external inputs, can be achieved by a combination of ecosystem processes and appropriate use of fertilizers. Figure 2 shows differences in nutrient inputs and outputs at three locations representing under-use, over-use and adequate use of fertilizers. Western Kenya is characterized by low inputs of N and P in marked contrast to the situation in China and the USA. The N outputs at the Kenyan site are much larger than the inputs, leading to substantial nutrient depletion or "soil mining" and consequent long-term degradation of soil health. On the other hand, high fertilizer nutrient inputs in China greatly exceed nutrient outputs and point towards substantial risks of nutrient losses to the environment. With almost similar inputs and outputs of both N and P, soil health in the Midwest USA is better than in either the Kenyan or Chinese sites. Soil quality is affected by nutrient availability as well as the potential for nutrients to degrade the environment. As soils represent a major store of reactive forms of nutrients, their sound management is critical to address global food security challenges as well as to minimize nutrient losses to the environment that can impact air and water quality. The other threats to soil health are many and varied (Velthof *et al.*, 2011): soil compaction, erosion, acidification, salinization, contamination, and organic matter decline, most of which can influence N and P losses to water and air.

Soils contain variable amounts of nutrients, which are needed by plants, animals and humans. Almost all nutrients in plants are taken up by roots from the soil, and primary production in many natural environments and agro-ecosystems is strongly limited by the availability of nutrients. This is especially the case in highly weathered and leached soils such as in large areas of Africa, Latin America, and Australia. Shortage of nutrients in soils leads to low crop yields and also to low contents of nutrients in the harvested crop; the sub-optimal nutrient concentration in crop produce may lead to malnutrition of animals and humans (Sanchez and Swaminathan, 2005). The elements N and P are often the most crop yield-limiting nutrients in agricultural soils. Most of the N is not directly available as it is organically bound although many irrigated soils with low SOM content can have much of the N in inorganic form in the profile. Most of the P is either organically bound or bound to iron and aluminium compounds, e.g., oxides and oxy-hydroxides.

Soils require a certain minimum level of plant-available N and P and other essential nutrients to fulfil the soil functions of food, feed and fibre production. However, a surplus supply of reactive N and P threatens the quality of the soil and results in the emissions of ammonia and N oxides to the air and loss of nitrate and P to water bodies (Velthof *et al.*, 2011). Excessive inputs of reactive N and P affect the quality of soils under forests and natural vegetation far more than that of agricultural soils

FIGURE 2

Total agronomic inputs and outputs of N and P in agricultural soils at Western Kenya, North China and Midwestern USA (data source: Vitousek *et al.*, 2009).



because withdrawal of N and P in harvested biomass is much smaller from forests and natural vegetation than from agriculture (Velthof *et al.,* 2011). As a consequence, relatively small inputs of reactive N and P lead to surpluses in forests and natural vegetation. Also, agricultural soils, unlike soils under forests and natural vegetation, are managed ones so that their disorders tend to be corrected even if the corrections are not always cost-effective. Application of excessive inputs of fertilizer P leads to the build-up of soil P to the point that the sorption capacity of the soil is eventually 'saturated'. The build-up of soil P can lead to increased losses of P to surface waters through overland flow, erosion and subsurface leaching and drainage.

In Sub-Saharan Africa, and in some other developing countries, soil health concerns, in as much as they are articulated, are due to poor nutrient supply in the soil. Two main factors underpin this concern. Firstly, increasing population pressures on agricultural land leads to a breakdown of traditional practices, resulting in much higher nutrient outflows. Secondly, there is generally a policy environment that does not give sufficient support to the small farmers to implement soil and cropping practices that could potentially reverse this depletion. A consequence of poor soil health is the high prevalence of food and nutrition insecurity due to lower agricultural production, less fodder for cattle, less fuel wood for cooking, and less crop residues and cattle manure to recycle nutrients to soils. Additional CO_2 emissions to the atmosphere are observed from decreasing soil and plant C stocks associated with soil nutrient depletion and deforestation. Also, in some soils, SOM levels have dropped even to a threshold below which crop response to other inputs is very poor.

FERTILIZER MANAGEMENT: SOIL HEALTH EFFECTS

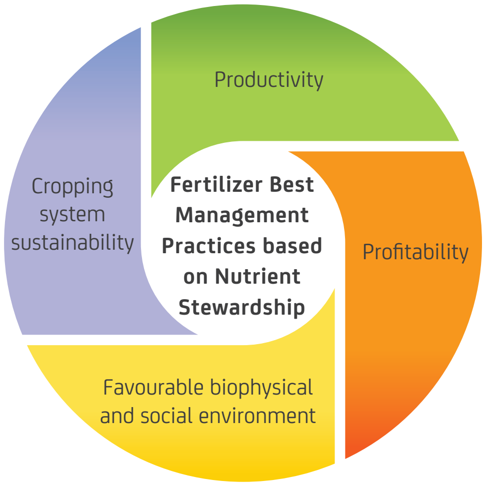
Where the supply of nutrients in the soil is adequate, crops are more likely to grow well and produce large amounts of biomass. Fertilizers are needed in those cases where nutrients in the soil are lacking and cannot produce healthy crops and sufficient biomass. There are four management objectives associated with any practical farm level operation, including management of fertilizers. These are ***productivity, profitability, cropping system sustainability,*** and a ***favourable biophysical and social environment***. Sustainability refers to the medium- and long-term effects of fertilizer management options to maintain or increase the productivity and profitability of the cropping system. Indicators include trends through time in yield, input use efficiency, soil parameters such as N supplying capacity, the presence of organic matter, and profitability. Best management practices for fertilizer support the realization of these objectives in terms of cropping and the environmental health (Bruulsema *et al.*, 2009). A strong set of scientific principles guiding the development and implementation of fertilizer best management practices has evolved from a long history of agronomic and soil fertility research. When seen as part of the global framework, the most appropriate set of ***fertilizer best management practices*** can only be identified at the local level where the full context of each practice is known.

Nutrient stewardship is the efficient and effective use of plant nutrients to achieve economic, social and environmental benefits with engagement from farmers and other stakeholders. This concept essentially describes the selection of the ***right source of nutrients*** for application at the ***right rate***, at the ***right time***, and in the ***right place*** (Roberts, 2007). Specific and universal scientific principles that apply to these four areas of management are applicable at the farm level. However, the application of these scientific principles may differ widely depending on the specific cropping system, the particular region and the crop combination under consideration. As a practice, nutrient stewardship is dynamic and evolves as science and technology expands our understanding and opportunities; practical experience teaches the astute observer what practices work or do not work under specific local conditions (Fixen, 2007). Decision-support systems guiding the adoption of fertilizer best management practices require a dynamic process of local refinement. Therefore, involvement of individuals knowledgeable in both scientific principles and local conditions is important to this process. As soils are at the heart of several sustainability issues facing humanity, management of fertilizers in cropping systems following principles of nutrient stewardship is the best approach to ensuring improvement in soil health due to application of fertilizers for crop production (Figure 3).

There are several causes of the declining or lower crop responses to applied fertilizers or efficiency of fertilizer applications in several developing countries. One major cause of this decline is the continuous nutrient mining of the soils (particularly P, K, sulphur (S) and micronutrients) resulting from ***unbalanced fertilization practices*** which eventually leads to unhealthy soils and plants. Therefore, fertilizers should be applied in sufficient quantities and in balanced proportions. The efficiency of fertilizer use is likely to be high where the organic matter content of the soil is also high. In unhealthy or depleted soils, crops use fertilizer supplied nutrients inefficiently. Where soils are highly degraded, like in parts of Sub-Saharan Africa, crops hardly respond to fertilizer applications. When SOM levels are restored, fertilizer can help maintain the revolving fund of nutrients in the soil by increasing crop yields and, consequently, the amount of residues returned to the soil. In a long-term experiment, the highest organic matter content in the soil has been observed in plots to which N, P and K were applied in a balanced proportion (Kumar and Yadav, 2001). In treatments receiving only N or inadequate amounts of P and K, there was a decline in soil health.

FIGURE 3

Fertilizer best management practices based on nutrient stewardship principles support the four management objectives that lead to improvement in soil health.



Site-specific nutrient management, whether based on nutrient status of soil or plant in a given field, ensures that nutrients applied via fertilizers are managed according to the needs of the soil-plant system. Thus, as compared to blanket fertilizer recommendations for different crops, which are still prevalent in several developing countries, site-specific nutrient management ensures that soil health is maintained on a long-term basis.

NITROGEN FERTILIZERS: POTENTIAL CONTRIBUTOR TO SOIL ACIDITY

Despite the positive effects of N fertilizers on crops, there can be indirect negative effects on soil health arising from natural transformations of N in the soil. The degree to which this natural phenomenon is a problem depends on the nature and amount of N fertilizer used and the soil properties. A key factor in the resilience of soil to pH change due to N transformation is the soil's buffering capacity, which, in turn, is dictated by the presence of solid-phase calcium carbonate. In arid and semi-arid areas of the world, soils are generally calcareous and thus highly buffered; in temperate regions soils tend to be neutral or slightly acid; while tropical soils are usually highly weathered and generally acidic, with little or no buffering capacity. The effect of continuous and excessive application of N fertilizers, particularly as reduced N (NH_3, NH_4^+), on soil health hinges on the extent of its effect on soil acidification.

During the acidification process, soils release base cations, such as calcium (Ca) and magnesium (Mg). Over time, and with continued addition of N, the base cations can be depleted and aluminum (Al^{3+}) is released from soil minerals, often reaching toxic levels that induce nutrient disorders in plants. Soil acidification due to application of N fertilizer depends upon the form of N added, the net balance between proton-producing and consuming processes, and the buffering capacity of the soil. Recently, Guo *et al.* (2010) reported severe soil acidification in China following application of heavy N fertilizer application rates. Between the 1980s and 2000s, soil pH was significantly reduced in large crop production areas. Fertilizer N application released 20 to 221 kg of hydrogen ion (H^+) per hectare per year, and base cations uptake contributed a further 15 to 20 kg H^+ ha^{-1} $year^{-1}$ to soil acidification. Continuing current fertilization practices in China is likely to be detrimental to soil health. Possibly using nitrate-based fertilizers and applying lime can help mitigate soil acidity.

Soil acidification indirectly leads to reduced microbial N immobilization (Venterea *et al.,* 2004). Soil acidification may also affect the decomposition and mineralization of SOM, and thereby SOM quality. Application of N fertilizers in excess of crop growth need leads to increased leaching of nitrate and cations (Ca, Mg) to groundwater, lakes and rivers, which affects the quality of these water bodies negatively. In the subsoil, the leached nitrate may contribute to the oxidation of pyrite, which releases sulphate and various trace elements including nickel (Ni), arsenic (As), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn) and zinc (Zn). Free-living fungi and N-fixing bacteria are sensitive to high reactive N levels and changes in the microbial community in turn impact soil processes like organic matter mineralization and nutrient cycling (Velthof *et al.*, 2011). A low soil pH promotes the production of nitrous oxide (N_2O), a potent greenhouse gas, via nitrification and denitrification.

Over the last century, an observed three- to five-fold increase in anthropogenic emissions of oxides of N (NO_x), nitrous oxide (N_2O) and ammonia (NH_3) has been attributed to fossil fuel burning and use of N fertilizers in intensive agriculture (Denman *et al.*, 2007). Due to the growth of the global population, leading to increased demand for food, particularly animal protein, NO_x, N_2O and NH_3 emissions are predicted to increase further in many regions. By 2100, N deposition over land may increase by a factor of 2.5 (Lamarque *et al.*, 2005). Along with emissions of NO_x from fossil fuel combustion, gaseous forms of N emanating from agricultural soils can have a detrimental impact on terrestrial ecosystems through soil acidification and a consequential reduction in plant biodiversity (Galloway *et al.*, 2003). The effects of soil acidification arising from excessive inputs of reactive N from atmospheric deposition have already been reported in soils under forests and natural vegetation. However, the unintended fertilization of forest ecosystems in the form of atmospheric N deposition can also stimulate forest growth as well as affect soil microbial activity and the cycling of C and nutrients in soils (Janssens *et al.*, 2010). The spill-over effects of N from agriculture to forests illustrate the inter-dependency of all components of terrestrial systems.

EFFECT OF FERTILIZER USE ON SOIL BIOTA

The beneficial functions provided by soil, i.e., ecosystem services, are driven by many interrelated and complex soil 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. As the soil system is an open one, its health or its integrity is affected by external environmental and anthropogenic or man-made pressures. Nutrients, applied as fertilizers or organic inputs, are a controlling input to the soil system and the processes within it. After C, the cycling of N and P and their dynamics or fluxes in soil have a controlling influence on delivery of ecosystem services, including agricultural production. Although manipulation of nutrient supplies to increase productive outputs from the soil system is fundamental to agriculture, knowledge is limited about the impacts of nutrient additions on the condition of different assemblages of soil organisms. However, with the rise of 'organic agriculture' in recent decades, there has been an emergence of concerns, real or imagined, about the impact of modern agricultural practices on the life within the soil. Arguments have been advanced that agricultural practices such as inadequate supply of C, energy, nutrients, and water, and, through the impact of intensive substitutive practices such as continuous mechanical tillage, and the use of pesticides, can impair the soil's natural functions. Claims have been made that excessive amounts of fertilizers (beyond crop needs) may impair soil health through significant but negative impacts on the composition and structure of the soil biological community.

It is generally considered that the availability of C substrate is the primary limiting factor on microbial activity in soils. However, this is not always the case as there is accumulating evidence that soil microbes may frequently be limited by the supply of N in the soil (Schimel *et al.*, 2005). When demand for N exceeds its supply, the functional capacity of the soil system is strongly influenced by N availability. Without additional inputs of N via inorganic fertilizers or organic manures, and particularly without due consideration of the associated C requirements of the biomass, soil health declines in agricultural systems. Similarly, the pool of P in soil is reduced through cropping or by erosion, resulting in soil health decline in the absence of any supplemental supply via fertilizers. Clearly, additions of animal manures and the use of mineral fertilizers can counter losses of N, P, and other nutrients – and help to restore and sustain soil health.

Agricultural interventions, such as the use of pesticides, over-use of inorganic fertilizers, and power tillage can affect biological communities in the soil by damaging their habitats and disrupting their functions (Kibblewhite *et al.*, 2008). Due to interactions between organisms and their functions, the link between disturbance, targeted biota and effect on function is far from linear. As most soil organisms depend directly or indirectly via one or more trophic levels on the processes of organic matter decomposition for their source of energy and C, any disruption of this energy-generating system may result in changes in the flow of energy and C to the different functions. However, assessment of the relative energy allocation to different functions may prove difficult due to integrating feature of the soil health system and probability of that any one soil organism can have multiple functions. For example, a substantial proportion of the organisms involved in nutrient cycling and soil structure maintenance are also primary or secondary agents of decomposition. Elucidation of these issues remains a major research challenge. It is evident that soil health in its functional sense should be seen, and managed, not as a set of individual soil characteristics, but as an integral property of the whole ecosystem. Nevertheless, numerous studies indicate that soil microbial activities, vital for the nutrient turnover and long-term productivity of the soil, are increased by inorganic fertilizer use and even further enhanced by integrated use of organic amendments along with inorganic fertilizers.

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The direct effects of fertilizer use on soil biota can be positive or negative and vary in duration depending on time-frame considered, the type and amount of fertilizer used and its manner of application. 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. In a study carried out in Australia, injection of urea and ammonia in bands reduced total microbial activity in narrow bands of application for a period of 5 weeks, after which levels returned to normal. There was 80% reduction in the number of protozoa, which had not returned to normal after 5 weeks. On the positive side, there was a large increase in the number of nitrifying bacteria in the soil 5 weeks after application of urea/ammonia in bands (Angus *et al.*, 1999). Recently, Geiseller and Scow (2014) published a meta-analysis based on 107 datasets from 64 long-term experiments from around the world and revealed that mineral fertilizer application led to a significant increase (15.1%) in the microbial biomass above levels in the unfertilized control treatments.

Fertilizer application tended to reduce microbial biomass in soils with a pH below 5 in the fertilized treatment but in experiments where soil pH was at least 7, the fertilization-related increase in microbial biomass averaged 48% (Table 1). Also, the increase in microbial biomass was the highest in studies that had been in place for at least 20 years. Biederbeck *et al.* (1996) recorded minimal impact on soil microbial populations and soil quality after 10 years of fertilization with urea and anhydrous ammonia. Mycorrhizal fungi have been consistently reported as being decreased by P fertilizer application but the extent to which this occurs depends on species of fungus involved and level of plant available P. Indirect effects of heavy use of N fertilizers on soil biota are usually longer-lasting and are due to changes in pH or changes in productivity, residue inputs and SOM levels. Given the conflicting reports on N and P effects of soil biota, more definitive studies are needed to clarify this issue.

TABLE 1

Soil microbial biomass carbon (mg kg^{-1}) in fertilizer nitrogen (+N) and unfertilized (-N) treatments. Unweighted averages are based on meta-analysis of 107 data sets from 64 non-lowland rice long-term experiments from all over the world (adapted from Geiseller and Scow, 2014).

	Number of data sets	Soil microbial biomass carbon (mg kg^{-1}) -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

FERTILIZER USE REDUCES SOIL EROSION

Much has been written about the role of man in causing soil erosion (Lal, 2007), but the connection between the various processes inherent in soil erosion (erosivity, erodibility[1]), and crop production practices, especially the use of mineral fertilizers, has not been well documented. In many tropical and subtropical locations, inadequate nutrient supply in the form of fertilizers and/or organic manures, and inappropriate management of nutrients quickly diminishes soil productivity and nutrient and organic matter-rich topsoil is lost by erosion. Insufficient nutrient availability in agricultural fields, e.g. due to fertilizer underuse in large parts of Sub-Saharan Africa, leads to loss of soil fertility and can lead to increased soil erosion due to inadequate plant cover. Biological N fixation and manure recycling are the only local nutrient sources which 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 increasing the risk of land degradation through erosion. 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 SOM. In such situations, the increased runoff and erosion losses contribute to sedimentation and siltation of reservoirs and coastal areas, and in some cases eutrophication of rivers and lakes.

[1] Erosivity is a description of the potential force, wind or rain, in a geographic area to erode existing soil.
Erodibility refers to the susceptibility of a particular soil to become detached and transported by wind, water, or ice.

FERTILIZER USE PROMOTES SOIL ORGANIC MATTER DECLINE – MYTH OR REALITY?

Much has been written about SOM as a key indicator of soil health because of its vital functions that affect soil fertility, productivity, and the environment. Given the fundamental coupling of microbial C and N cycling, the dominant occurrence of both elements in SOM, and the close correlation between soil C and N mineralization, the practices that lead to loss of soil organic C also have serious implications for the storage of N in soil. Considerable evidence from ^{15}N-tracer investigations indicates that plant uptake is generally greater from native soil N than from N applied via fertilizers (Stevens *et al.*, 2005). Thus, native soil N dictates the efficiency of applied fertilizer N as well as the quantity of N lost from the soil-plant system. Loss of organic N decreases soil productivity and the agronomic efficiency of fertilizer N and has been implicated in yield stagnation and the decline of grain production (Mulvaney *et al.*, 2009). A decrease in soil N supply is inherently detrimental to productivity. Crop yields may be sustained or even increased by using improved varieties or due to higher fertilizer application rates despite the lower incremental return per unit of N applied, but eventually, soil degradation is likely to lead to a decline or stagnation in yield, an emerging concern for input-intensive agriculture.

Various studies have shown that SOM changes with cultivation and fertilizer N inputs; this is an issue that has become increasingly controversial. Normally, SOM decreases with cultivation where no N fertilization is practiced, but it may increase with application of N fertilizer. Potentially, fertilizer N application affects SOM via two mechanisms:

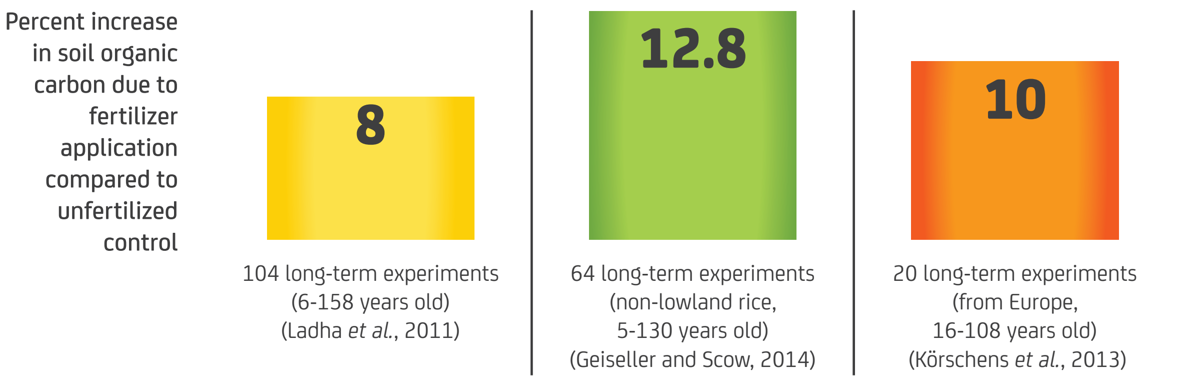
(i) it may increase SOM by promoting plant growth and thereby increasing the amount of litter and root biomass added to soil compared with soil not receiving N, and

(ii) it may accelerate SOM loss through decay or microbial transformation of litter (leaves, straw, manures, etc.) and indigenous forms of organic C already in the soil (Recous *et al.*, 1995). The first mechanism is widely accepted, but the second mechanism has not been demonstrated indisputably.

On the basis of the results of 45 long-term experiments ranging from 7 to 136 years in duration and mostly from temperate regions, Glendining and Powlson (1995) showed that long-term applications of N fertilizer increased total soil organic N compared with treatments receiving no fertilizer N at 84% of the sites studied. On the other hand, in long-term experiments located in both temperate and tropical regions, continuous application of fertilizer N induced a net loss of soil organic N at 92% of the sites examined and a loss of soil organic C at 74% of the sites (Khan *et al.*, 2007, Mulvaney *et al.*, 2009). Powlson *et al.* (2010), however, argued that past changes in the input of manures and synthetic fertilizer N, as well as long-term changes in soil N and C in the no-N control plot need to be taken into consideration when interpreting changes in total organic N and C in the soil. These authors also questioned whether the data set used

FIGURE 4

Increase in soil organic carbon due to fertilizer application compared to unfertilized control in long-term experiments from all over the world.



by Khan *et al.* (2007) and Mulvaney *et al.* (2009) was comprehensive enough to support the conclusion that synthetic fertilizer N caused a decline in organic C and N fractions.

A pressing question of importance to global agriculture and food production was: Does the long-term use of synthetic fertilizer N lead to a decline in SOM in soils? Ladha *et al.* (2011) attempted to resolve this controversy by collecting data from 114 long-term experiments located all over the world and concluded that the approach followed by Khan *et al.* (2007) and Mulvaney *et al.* (2009) does not take into account the changes in organic C and organic N over time when no fertilizers were applied. The absolute change in total soil organic C and N after long-term fertilizer N application, as reported by Khan *et al.* (2007) and Mulvaney *et al.* (2009), follows the time-response ratio, and thus shows a decline. However, when the data were analysed following time by fertilizer N response ratio, declines of 7 to 16 % in organic C and 7 to 11% in organic N were found with no N amendments; however, with soils receiving fertilizer N, the rate of SOM loss decreased. The time by fertilizer response ratio approach based on changes in the paired comparisons showed average increases of 8 and 12 % for organic C and organic N, respectively. Along with Ladha *et al.* (2011), recently Geiseller and Scow (2014) and Körschens *et al.* (2013) found that, in long-term experiments from all over the world, adequate and balanced use of mineral fertilizers resulted in an increase in SOM as compared to plots receiving no fertilizers (Figure 4). If a decline in SOM following the application of synthetic fertilizer N would have been a general phenomenon, it almost certainly would have major consequences for food production as it would have resulted in a spiral of decline in soil functioning and crop productivity.

INTEGRATED MANAGEMENT OF FERTILIZERS AND ORGANIC NUTRIENT SOURCES

The use of organic manures as source of nutrients and its general benefit to the soil dates back to the beginning of settled agriculture, although at that time there was no understanding of how such manures were beneficial. Following the introduction of high-yielding cereal varieties and widespread use of mineral fertilizers that provided N, P, and K as the primary plant nutrients, organic manures were thought of as a secondary source of nutrients. However, with increasing awareness about soil health and sustainability in agriculture, organic manures and many diverse organic materials, have gained importance as components of integrated plant nutrient management (IPNM) strategies. Consequently, major focus in sustainable agricultural systems is on the management of SOM and plant nutrients through integrated use of mineral fertilizers with organic inputs such as animal manures, biological N fixation, crop residues, green manures, sewage sludge, and food industry wastes. The basic concept underlying IPNM is the maintenance and possible improvement of fertility and health of the soil for sustained crop productivity on long-term basis and use fertilizer nutrients as supplement to nutrients supplied by different organic sources available at the farm to meet the nutrient requirement of the crops to achieve a defined yield goal.

TABLE 2

Mean yield of wheat and changes in soil organic carbon after application of mineral fertilizers, farmyard manure and their combination in a 9-year experiment on irrigated wheat-soybean cropping system in an Alfisol at Almora in the sub-temperate region of North India (adapted from Bhattacharyya *et al.*, 2010).

Treatment		Mean yield of wheat over 9 years (t ha^{-1})	Soil organic carbon content in 0-15 cm top soil (t ha^{-1}) after 9 years
N-P-K (kg ha^{-1})	Farmyard manure (t ha^{-1})		
0-0-0	0	1.30	14.10
0-0-0	10	1.71	15.44
120-26-33	0	2.40	16.91
120-26-33	10	3.04	18.62
LSD (p = 0.05)		0.21	1.89

Integrated soil fertility management (ISFM) is defined as a set of soil fertility management practices that necessarily include the use of fertilizer and organic inputs as well as improved germplasm, combined with the knowledge of how to adapt these practices to local conditions. Such practices are aimed at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles (Vanlauwe *et al.*, 2010). Fertilizers constitute an entry point for following ISFM, which is a very field-specific strategy. The goal of ISFM is to maximize the interactions that result from the potent combination of fertilizers, organic inputs, improved germplasm, and farmer knowledge. The ultimate outcome is improved productivity, enhanced soil quality, and a more sustainable system through wiser farm investments and field practices with consequent minimal impacts of increased input use on the environment. The IPNM and ISFM approaches are holistic and seek to optimize plant nutrient supply with an overall objective of adequately nourishing the crop as efficiently as possible, and improving and maintaining the health of the soil base while minimizing potentially adverse impacts to the environment. For example, in a 9-year study on wheat-soybean cropping system in an Alfisol in the sub-temperate region in North India, productivity of wheat was significantly increased and soil health in terms of soil organic carbon content was improved by combined application of organic manure and mineral fertilizers (Table 2).

Despite the characteristic pattern of SOM depletion, there is seldom a stage of complete exhaustion, even under tropical conditions which favour rapid organic matter decomposition; in fact, heavily cultivated soils tend to attain a steady state at a lower equilibrium limit (Buyanovsky and Wagner, 1998). In virgin or previously uncultivated soils, SOM levels are the highest for that particular environment; thus equilibrium SOM levels are environment-specific. Cultivation invariably reduces SOM levels to an extent that depends on management and inputs. In well managed cultivated soils, soil organic C fluctuated between a low steady state value of SOM in the heavily cultivated soil and the highest value observed in the uncultivated soil; cultivation alone tended towards the lower equilibrium soil C levels, but the addition of manures with fertilizers reduced the extent of SOM decline with cultivation. As environmental conditions differ worldwide, as well as agricultural productions systems with respect to organic inputs, some broad regional observations with respect to SOM levels are pertinent.

Deficiency of SOM is widespread in tropical soils and particularly those under the influence of arid, semiarid and sub-humid climates due to the controlling influence of climatic factors on primary productivity and biomass decomposition. Since sustainability is not possible without equalizing the nutrient removals and additions, productivity without fertilizers declines steadily. In temperate regions, crop residues are routinely incorporated into the soil, but the practice of returning residues to the soil is practically non-existent in tropical regions. Thus, in the tropics, low organic matter additions as well as accelerated degradation and loss due to year-round prevalence of biologically active temperature and moisture regimes leads to rapid reductions in SOM levels and consequently reduced soil health due to the absence of the beneficial effects of the organic matter. In general, the SOM content of tropical soils, when brought under cultivation, can fall to as low as about 30% of the original value of the uncultivated indigenous state, but most reports indicate about a 60% reduction after 10 years of cultivation. Katyal *et al.* (2001) documented such changes with arable cropping from long-term field experiments. In a virgin soil, SOM remained stable for 10 years after fertilizer application, but subsequently fell to about 40% of the initial value during the next 3 years. However, when manures and fertilizer were applied, the SOM level was stable for 25 years, thus illustrating the value of integrated use of organic and inorganic nutrient sources in stabilizing and maintaining SOM in cropping systems and ensuring sustainability regardless of the cropping system. Under irrigated conditions and regular application of recommended application rates of NPK fertilizers, productivity stagnated or declined after initially increasing for 5-6 years. It was the combined application of fertilizers and farmyard manure that unfailingly sustained productivity. This conclusion was valid, irrespective of the location or the cropping system (Katyal *et al.*, 2001).

In addition to its physical and biological functions in soils, the application of organic manures has incidental effects on nutrients other than the major ones, e.g. by reducing or eliminating the emergence of micro- and secondary nutrient deficiencies and preventing a fertilizer-induced drop in pH of poorly buffered acid soils. Even under rainfed conditions, in which fertility and productivity of soils is depleted to such an extent that fertilizer application was indispensable for getting an immediate boost in yield, the addition of organic manure was necessary to sustain the yield rise thus obtained. Thus, IPNM based on fertilizers and organic manures is essential to sustain high productivity and good soil health.

In Africa, where soils are highly degraded in terms of loss of organic matter and nutrient mining, sustainable nutrient and organic matter management is emerging in the form of ISFM. The concept of ISFM is now an accepted and proven approach to soil and crop management (Alley and Vanlauwe, 2009). When using fertilizers along with organic inputs following ISFM principles in Africa, two types of soils are recognized in terms of response to fertilizers:

(i) soils in which crop productivity responds to fertilizer – 'responsive soils', and

(ii) soils in which crop productivity does minimally or not respond to fertilizer – 'poor, less-responsive soils' (Vanlauwe *et al.*, 2011).

Discontinuous, insufficient or no fertilizer application over a certain period of time may lead to severe soil degradation through nutrient depletion and loss of SOM, making soils non-responsive to fertilizers. When fertilizer or organic matter applications restart after a certain period of cultivation, soils may not respond immediately and crop productivity may not be raised back to the yields attained before fertilizer use was interrupted.

Reversibility may be lost when a certain threshold of soil degradation is surpassed. This effect has been termed 'soil memory' and related to the parameters that define response curves to fertilizers by crops (Tittonell and Giller, 2013). Characterising the determinants of such soil memory, and ways to overcome it to ensure soil rehabilitation or resilience for different types of soils and cropping systems is a challenging task. For example, Zingore *et al.* (2007) demonstrated that responses to fertilizer on degraded outfields were only obtained after application of 17 t ha^{-1} year^{-1} of farmyard manure during 3 consecutive years. Once soils became responsive to fertilizers, IPNM based on the combined application of organic inputs and fertilizer resulted in improvement in agronomic efficiency as well as soil health. This unique interaction of organic manures and fertilizers is an important consideration in dealing with soils of developing countries which generally tend to be degraded by comparison with soils in developed countries that have a longer history of fertilizer use.

RESEARCH NEEDS

- While concepts of soil health are still vague—and evolving—it is clear that future research on various aspects of fertilizer use in crop production and cropping systems will need to consider soil aspects in addition to the primary focus of crop yields. But it might be hard to procure funding for soil health research unless it can be in some way related to improving cropping, either in terms of increased yields or using inputs more efficiently.
- While many properties reflect soil health or quality, there is no one operationally defined integrated index of soil health. Although studies of soil health hinge upon organic matter content of soils, nearly all deal with total SOM rather than more reactive labile or biomass C fractions that purportedly are more sensitive indicators of changes in SOM.
- In terms of fertilizer effects on soil health, the focus has been almost exclusively on N and to a much lesser extent on P; the role of K, secondary nutrients or micronutrients on soil health has not been explored, although it is likely that such nutrients will have minor effects compared to the major nutrients.
- With respect to soil health, there needs to be greater documentation of the stability of SOM and the fate of organic residues in the long-term in various cropping systems. In that respect, many long-term agronomic experiments in different agro-ecological zones across the world can provide invaluable datasets pertinent to soil quality.
- While soil health-related studies have been reported from various climatic regions of the world, the specific effects of rainfall or soil moisture and soil temperature on soil health has not emerged. Modeling could be usefully employed in this regard.
- Given the limited and sometimes conflicting reports of fertilizers in relation to soil health, combined with the lacuna in identifying many soil organisms, there is a clear need to reconcile conflicting data and to explore the unknown in the microbial kingdom.
- Response of different microbial groups to repeated applications of mineral fertilizers varies and seems to depend on environmental and crop management related factor. As enough data are not available to understand the interactions among environmental factors, fertilizer rates and types and specific groups of soil microorganisms, there is need to conduct more studies to understand these complex interactions.
- While several studies have identified crop residues and other organic material in terms of their effects on soil health, a range of residues need to be considered, from soluble and readily decomposable legumes to lignified resistant material in cereal straw.
- In the quest of reducing cost of cultivation and possibly maintaining and/or improving soil health, in many parts of the world there is increasing trend to adopt conservation agriculture systems in which soil is tilled to the minimum extent and crop residues are retained in the soil so as to help build up of SOM. There is need to establish appropriate fertilizer management strategies in such systems so that soil health is maintained or improved.
- As called for in this International Year of Soils, at the broad societal level, there needs to be a greater public awareness of the importance of soil in terms of how it affects mankind through primary crop production, how it impacts the amount and quality of our food, and thus our health, how it impacts our water and environment, how it mediates greenhouse gases and climate change, and how it dictated the course of civilization itself.

SUMMARY AND RECOMMENDATIONS

Soil is fundamental to life on Earth. Fertilizers are the main factor responsible for providing adequate food for the world's current population of over 7 billion people; fertilizers will be even more important in sustaining the over 9 billion people projected for 2050. While the primary impact of mineral fertilizers is on crop yields, they also have an indirect effect on the soil in terms of quality or health or its capacity function for the betterment of mankind.

Many factors contribute to soil quality or health. Favorable physical factors such as texture are an important component of quality but texture is largely unchangeable. The key factor in quality is the SOM fraction, which although relatively small, has a strong influence on the overall wellbeing of the soil and its beneficial functions. Soil organic matter controls soil microbial populations and their many functions in soil such as decomposition and nutrient cycling. Fertilizer use can have positive or negative effects on soil health. Depending on the tillage system used, regular additions of N fertilizer can enhance SOM levels. Organic matter can help increase soil aggregate stability and thus contribute to resistance to erosion and soil degradation.

While the natural transformations of N fertilizers in soil can induce acidity, and thus lower soil pH, with negative impact on crop growth, the extent of this effect depends on the amount and form of N used and the type of soil; calcareous soils are resilient or buffered against such effects. The negative effects of fertilizer on soil microbial populations depend on the N source and method of application, but negative effects are localized and short-lived. Long-term use of fertilizers leads to increases in soil microbial biomass.

The extent to which mineral fertilizers 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 best management practices. These principles call for the integrated use of organic manures with mineral fertilizers whenever possible.

As with many other areas of science, there needs to be a more concerted effort to educate the public at large on the synergy between fertilizers in relation to crop yields and quality or health of the soil. Soil and agronomic research has clearly shown that that sustainable agricultural intensification and a healthy environment are compatible goals.

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