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A REVIEW :

Strategies to improve soil fertility to sustain agriculture

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BACKGROUND AND OBJECTIVES

Healthy soil is the foundation of the food system. The natural resource base of agriculture, which provides for sustainable production is shrinking, degrading and is adversely affecting the production capacity of the ecosystem. Soil health, is the most valuable resource for humans, as human life depends on the soil's generosity. Soil degradation, therefore, poses a threat to food security, asit reduces yield, forces farmers to use more inputs, and may eventually lead to soil abandonment (Tiziano Gomiero, 2016). The sustainable production (availability) of food is increasingly threatened through impacts deriving from human activities, especially changing forms of land use at local and global scales. These changes are frequently human induced or human influenced (Foley *et al.*, 2005). Most critical are soil losses through sealing by urbanisation, industrialisation and transport, probably the most important threat to food security of all, but also erosion by water and wind and further severe forms of soil degradation, such as loss of organic matter, contamination, loss of soil biodiversity, compaction, salinisation, flooding, nutrient mining and desertification (Winfried, 2013). Agricultural activities have a clear impact on global environmental change (Tilman *et al.*, 2011). Moreover, climate change is threatening food security directly through increasing losses and degradation of soil, mainly through extreme events and in many regions a decrease of water resources is threatening rain-fed and irrigation agriculture. Without new approaches in land and water conservation at local and worldwide levels, it has to be expected that within one or two decades food shortage will severely further threaten millions of people and increase hunger, especially in developing countries (Winfried, 2013).

Soil is an essential non-renewable resource with potentially rapid degradation rates and extremely slow formation and regeneration processes (Van-Camp *et al.*, 2004). Soil degradation is as old as agriculture itself, its impact on human food production and the environment becoming more serious than ever before, because of its extent and intensity. Reduced precipitation or increased temperature accelerates land degradation through the loss of plant cover, biomass turnover, nutrient cycling and soil organic carbon storage, accompanied by higher greenhouse emissions (Duran and Rodríguez, 2008). There is a strong link between soil degradation and desertification on the one hand and risks of accelerated greenhouse effects and climate change on the other (Komatsuzaki and Ohta, 2007).

Causes for soil deterioration :

Decline in soil organic matter :

Soil organic matter content is a function of organic matter inputs (residues and roots) and litter decomposition. It is related to moisture, temperature and aeration, physical and chemical properties of the soils as well as bioturbation (mixing by soil macrofauna), leaching by water and humus stabilization (organomineral complexes and aggregates). Organic matter plays a central role in maintaining many key soil functions and is a major determinant of a soil's resistance to erosion and underlying soil fertility (Lal, 2002). Land use and management practices also affect soil organic matter. Farming systems have tended to mine the soil for nutrients and to reduce soil organic matter levels through repetitive harvesting of crops and inadequate efforts to replenish nutrients and restore soil quality. There is evidence that with a shift in the last half century towards greater specialisation and cereal monoculture particularly in temperate regions, losses of soil organic matter through decomposition are often not completely replaced. This decline continues until management practices are improved or until a fallow period allows a gradual recovery through natural ecological processes. Specialisation in farming has led to the separation of livestock from arable production so that rotational practices which were important in the past in maintaining soil organic matter content no longer exist.Moreover, carbon as a major component of soil organic matter plays a major role in the global carbon cycle. Only carefully selected diversified cropping systems or well-managed mixed crop–livestock systems are able to maintain a balance in nutrient and organic matter supply and removal (Alexandra and Benites, 2005).

Soil nutrient mining:

Countries around the world have made rapid growth in fertilizer consumption, particularly after the introduction of High Yielding Varieties. Increased fertilizer consumption has been instrumental to get higher yields and helped to improve agricultural productivity and farm income in the countries. Soil nutrient mining is possibly one of the most significant threats to food production in large parts of the tropics. Increasing pressure on land through both rising population and in some countries exclusion of indigenous populations from parts of the landscape through land grabbing has resulted in a reduction in the length of fallow periods and in some cases their removal.Nutrient balances which consider the inputs and outputs from the system have been used to estimate the magnitude and extent of nutrient mining. India, despite being the second largest user of fertilizers, the per hectare fertilizer use in India is still low and imbalanced. The NPK use ratio in 2009-10 was 4.3:2.0:1 which has widened to 6.7:3.1:1 in 2011-12 and it has been further distorted in 2012-13 against the desired ratio of 4:2:1 (Chander, 2013). This soil fertility depletion due to imbalanced and inefficient use of fertilizers has become a serious constraint not only in improving yields and farmers' profits but poses a serious threat to the environment. Further, negative NPK balance in soil between crop removal and fertilizer addition has been around 8 to10 million tonnes per year. In addition, the recent escalation in fertilizer prices has severed a setback to the concept of balanced fertilisation. Economic rationality, therefore dictates a more comprehensive approach to fertilizer utilisation incorporating soil tests, field research and economic evaluation of results.

Impact of human activities on soil:

Most of the threats to land and soil arise because we expect the soil to perform a range of functions. By steadily increasing the demands on the soil from these functions we have often created an unstable system where the soil becomes less resilient and more vulnerable (Lal, 2007). These threats are increasingly seen as particularly relevant to the biomass production function of soils, and hence, impact global food security.

Soil sealing through urbanisation and industrialisation :

Urbanisation and industrialisation has led to the establishment of infrastructure for modern life, housing, roads or other land developments. This leads to land sealing making the soil unable to perform many of its functions including the absorption of rainwater for infiltration, and filtering in general. In addition sealed areas may have a great impact on surrounding soils by changing water flow patterns. Soil sealing is almost irreversible and there is increasing concern amongst governments and environmental regulators at this permanent loss of soil and the associated loss of ecosystem functions.

A novel manner in which the extent of soil sealing may be viewed is by examining the view of the Earth from space at night with the lights associated with urban development visible. Fig. 1 shows a recent example of the night time view of the Earth. Whilst not an exact correspondence it is also clear that much of the higher quality land is also associated with the areas of highest levels of urbanisation. There is clear evidence of high levels of urbanisation in North America, Western Europe and Japan (The Earth Institute, 2005), areas frequently strongly associated with good quality land. But this image also highlights some recent changes such as the increasing urbanisation in the Indian sub-continent and China. Any further extension of urban growth will occur on best soils because our ancestors had chosen those soils for their first settlements. An estimation of current daily losses of soil through urbanisation, industrialisation and transport in the European Union (total surface 4, 324, 782 km^2) amounts to about 1, 200 ha per day, corresponding to 12 km^2. A very rough estimation of daily soil losses at the global scale amounts to about 25, 000 — 30, 000 ha per day, corresponding to 250 — 300 km^2.

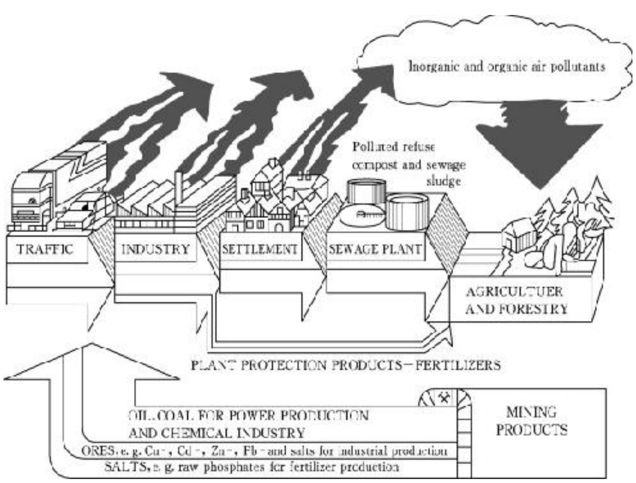

Fig. 1 : Soil contamination through excessive use of fossil energy and raw materials (Blum, 1988)

The reason for the earth's increased temperature along with change in rainfall amount and distribution, must be sought in the use of fossil fuel, that has drastically disturbed the global carbon cycle with its attendant impact on climate change. According to Komatsuzaki and Ohta (2007), there is also evidence that continuous cropping and inadequate replacement of nutrients, removed in harvested materials or lost through erosion, leaching and gaseous emissions, degrade soil physical, chemical and biological properties, intensifying global warming. Moreover, the production of urban and industrial organic wastes is increasing worldwide and strategies for disposal in such a way that these do not further degrade soil, contaminate water or pollute air must be developed and optimized (During and Gath, 2002; Lal, 2008).

Strategies to improve soil fertility and sustain agricultureSoil fertility :

Soil fertility can be defined as the capacity of soil to providephysical, chemical and biological needs for the growthof plants for productivity, reproduction and quality, relevant toplant and soil type, land use and climatic conditions (Murphy, 2007). It is becoming understandable that theproper agricultural use of soil resources requires equal considerationfor biological, chemical and physical components ofsoil fertility, thus attaining a sustainable agricultural system.

Sustainable agriculture:

The term "sustainable agriculture" is used in this reviewwith the meaning given by Tilman *et al*. (2002), as referring topractices that meet current and future society needs for foodand feed, ecosystem services and human health, maximizingthe net benefit for people. Namely, sustainability implies bothhigh yields, that can be maintained, and acceptable environmentalimpact of agricultural management. Losses of soil organic matter can be reversed with the adoption of land management practices such as conservation tillage, including no tillage cropping techniques, organic farming, permanent grassland, cover crops, mulching and manuring with green legumes, farmyard manure and compost.

Practise of organic farming:

It is relevant to note that organic farming is the only sustainableform of agriculture legally defined. One of the possible main tools for the maintenanceand the improvement of soil fertility in organic farmingis to adopt crop rotations, including a mixture of leguminousfertility-building crops and plants with different rooting depths(Watson *et al.*, 2002). Furthermore, organic wastes such asanimal manures, by-products of several kinds and compostedresidues can be used as amendments to increase soil fertility, since they are important sources of nutrients for growing cropsand means for enhancing the overall soil quality (Davies and Lennartsson, 2005). Sustainable practices providing organic amendments could be a useful tool to maintain or increase organic matter content in agricultural soils, preserving and improving soil fertility. An improved knowledge of management factors affecting soil quality is crucial to plan farming systems that effectively maintain soil fertility. Therefore, this review focuses on the potential value of organic amendments in the recovery of soil fertility, in particular in sites under plastic cover intensive farming system. Following a brief overview of the effects of intensive agriculture on soil, the review describes various organic amendments used in agriculture and their benefits on soil fertility, to conclude with the need, in the future researches, to identify organic amendments able to maximize a recovery of soil fertility (Scotti *et al.,* 2015).

Improving the soil organic matter status:

Soil organic matter plays an important role in long-term soil conservation and/or restoration by sustaining its fertility, and hence in sustainable agricultural production, due to the improvement of physical, chemical and biological properties of soils (Sequi, 1989). The organic matter content is the result of the inputs by plant, animal and microbial residues, and the rate of decomposition through mineralization of both added and existing organicmatter. More specifically, the generic term "organic matter" refers to the sum of all organic substances present in the soil. This sum comes from residues at various stages of decomposition, substances synthesized through microbial-chemical reactions and biomass of soil microorganisms as well as other fauna, along with their metabolic products (Lal, 2007). Decomposition of organic matter is chiefly carried out by heterotrophic microorganisms. This process is under the influence of temperature, moisture and ambient soil conditions and leads to the release and cycling of plant nutrients, especially nitrogen (N), sulfur and phosphorus (Murphy *et al.,* 2007).

The different fractions of organic matter undergo the "humification" process, which is the changing from recognizable parts and pieces of plants or animals into an amorphous, rotted dark mass. The products of humification are the humic substances that in soil are dark brown and fully decomposed, *i.e.* humified. The humic substances are one of the most chemically active compounds in soils, with cation and anion exchange capacities far exceeding those of clays. They are long-lasting critical components of natural soil systems, persisting for hundreds or even thousands of years (Mayhew, 2004). In fact, the turnover rate of organic materials varies considerably, from less than 1 year, as for microbial biomass, to more than one thousand years of stable humus (Van-Camp *et al.*, 2004). Within this context, soil fertility could also be improved with organic waste application such as by-products of farming, or municipal activities including animal manures, food processing wastes and municipal biosolids, wastes from some industries, such as sewage sludges, wastewaters, husks and vinasse. Both groups of wastes present generally notable contents of organic matter and substantial quantities of nutrients and their use in agriculture can contribute to closing the natural ecological cycles (Montemurro *et al.*, 2004; Montemurro and Maiorana, 2008). Increased recycling of organic residues as fertilizers and soil amendments on cropland avoids both utilization of non-renewable resources, e.g., fossil fuel and peat, and excess of energy expenses, *i.e.*, production of chemical fertilizers and pesticides, treatment and landfill disposal of such organic wastes (Mondini and Sequi, 2008). Biodegradable wastes can also be considered valuable resources to promote soil fertility.

Increased use of compost:

A diverse range of organic matter is the best way to improve soil fertility. Firstly, manure should be added for nitrogen, which is a critical component of fertile soil. Livestock manure (cow, goat, pig) is a good option. Manure from unhealthy and confined animals is more likely to have pathogens which may contaminate your crops. Even with manure from healthy animals, make sure to wait at least three months between before applying the manure. This will guard against contamination. Another great source of nitrogen for your garden is compost. Compost has the added benefit of helping to break up clay particles, allowing water to drain better. Additionally, in sandy loam it binds the grains together to reduce moisture, making the soil more fertile.

Compost is a stabilized and sanitized product of composting, which is the biodegradation process of a mixture of organic substrates carried out by a microbial community composed of various populations, both in aerobic conditions and solid state (Insam and de Bertoldi, 2007). The soil application of co-composted manure has several advantages over fresh manure, such as reduced numbers of viable weed seeds, reduced volume and particle size, which facilitates land distribution, a better balanced nutrient composition, stabilized organic matter and a slower release of nutrients. This topic has recently been reviewed by Moral *et al.* (2009).

Mixed cropping:

A lesser-known way to improve soil fertility is to plant different crops in the same field in order to preventsoil erosion and control the spread of soil-borne plant disease. Doing this with legumes will have the benefit of adding nitrate to the soil. Try to use deep rooted vegetables, which will improve soil fertility naturally.

Mulching or incorporation cover crops:

Soil fertility can be further improved by incorporating cover crops that add organic matter to the soil, which leads to improved soil structure and promotes a healthy, fertile soil; by using green manure or growing legumes to fix nitrogen from the air through the process of biological nitrogen fixation; by micro-dose fertilizer applications, to replenish losses through plant uptake and other processes; and by minimizing losses through leaching below the crop rooting zone by improved water and nutrient application. Mulch is a way to cover the soil which helps retain water, control weeds and prevent erosion, thus improving soil fertilityu. Plant wastes can be used as mulch.Mulch should not be too thick, as this may have the effect of holding too much moisture and causing plant diseases.

The contribution of nuclear and isotopic techniques:

Nuclear techniques provide data that enhances soil fertility and crop production while minimizing the environmental impact. The isotopes of nitrogen-15 and phosphorous-32 are used to trace the movements of labelled nitrogen and phosphorous fertilizers in soils, crops and water, providing quantitative data on the efficiency of use, movement, residual effects and transformation of these fertilizers. Such information is valuable in the design of improved fertilizer application strategies. The nitrogen-15 isotopic technique is also used to quantify the amount of nitrogen fixed from the atmosphere through biological nitrogen fixation by leguminous crops (*www.iaea.org/topics/improving-soil-fertility*)

The carbon-13 isotope signature helps quantify crop residue incorporation for soil stabilization and fertility enhancement. This technique can also assess the effects of conservation measures, such as crop residue incorporation on soil moisture and soil quality. This information allows the identification of the origin and relative contribution of different types of crops to soil organic matter.

The Joint FAO/IAEA Division assists Member States in developing and adopting nuclear-based technologies for improving soil fertility practices, thereby supporting the intensification of crop production and the preservation of natural resources.

Inclusion of organic amendments and itslong-term effects soil fertility:

The intensity of cultivation increase the rate of decomposition (Montemurro *et al.*, 2007). By contrast, the build-up of organic matter in soils is a process much slower and more complex than its decline (Van-Camp *et al.*, 2004). Since organic matter contents are difficult to measure directly, a great number ofmethods measure the soil organic carbon level, multiplying it by conversion factors ranging from 1.7 to 2.0 to obtain organic matter values (Baldock and Nelson, 2000).As a consequence, agricultural management practices that enhance soil organic matter content are used for preserving farming output and environmental quality; thereby they can be considered as sustainable activities.

Common agricultural practices such as excessive use of agro-chemicals, deep tillage and luxury irrigation have degraded soils, polluted water resources and contaminated the atmosphere. There is increasing concern about interrelated environmental problems such as soil degradation, desertification, erosion, and accelerated greenhouse effects and climate change. The decline in organic matter content of many soils is becoming a major process of soil degradation, particularly in European semi-arid Mediterranean regions. Degraded soils are not fertile and thus cannot maintain sustainable production. At the same time, the production of urban and industrial organic waste materials is widespread. Therefore, strategies for recycling such organic waste in agriculture must be developed. Here, we review long-term experiments (3–60 years) on the effects of organic amendments used both for organic matter replenishment and to avoid the application of high levels of chemical fertilizers.

Integrated soil fertility management approach:

Advancing food security and environmental sustainability in farming systems requires an integrated soil fertility management approach that maximizes crop production while minimizing the mining of soil nutrient reserves and the degradation of the physical and chemical properties of soil that can lead to land degradation, including soil erosion. Such soil fertility management practices include the use of fertilizers, organic inputs, crop rotation with legumes and the use of improved germplasm, combined with the knowledge on how to adapt these practices to local conditions.An integrated soil fertility management aims at maximizing the efficiency of the agronomic use of nutrients and improving crop productivity.

This can be achieved through the use of grain legumes, which enhance soil fertility through biological nitrogen fixation, and the application of chemical fertilizers.Whether grown as pulses for grain, as green manure, as pastures or as the tree components of agro-forestry systems, a key value of leguminous crops lies in their ability to fix atmospheric nitrogen, which helps reduce the use of commercial nitrogen fertilizer and enhances soil fertility. Nitrogen-fixing legumes are the basis for sustainable farming systems that incorporate integrated nutrient management. Use of nitrogen-15 lends understanding of the dynamics and interactions between various pools in agricultural systems, including nitrogen fixation by legumes and utilization of soil and fertilizer nitrogen by crops, both in sole and mixed cropping systems.Conservative soil tillage systems, e.g. no-till, which leavesmore residues on the surface because the soil is not turnedover, can maintain or improve the organic carbon content andthe related soil fertility properties (Ismail *et al.*, 1994 and Johnson *et al*., 2005).

The inclusion in a rotation of cover crops or green manurescan also enhance the efficient use of nutrients by plants,mainlyowing to the increase in soil microbial population and activity (Watson *et al.,* 2002). Cover crops are generally grown to providesoil cover during the winter months, thus, preventing soilerosion by wind and rainwater strength, which reduces organicmatter content in the long run. In particular, leguminous green manurescan fix large quantities of atmospheric N_2. They also provideuseful amounts of organic matter, as well as non-leguminouscrops which, nevertheless, cannot fix atmospheric N_2 (Davies and Lennartsson, 2005).

Agroforestry and the improvement of soil fertility:

The use of diverse tree species and other practices employed in agroforestry systems can represent alternative forms of increasing soil fertility and maintaining agricultural production, withimportant practical applications for the sustainability of tropical agriculture.(Rachel *et al.*, 2012). “Agroforestry is a collective name for landusesystems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components”

According to a study by the World Agroforestry Centre, ICRAF, 43% of the planet’s agricultural lands (more than abillion hectares) has more than 10% tree cover. A lesserbut still significant area of agricultural land, 160 millionhectares, has more than 50% tree cover. The potential oftrees to bring improvements in nutrition, income, housing, health, energy needs and environmental sustainability in theagricultural landscape has guided ICRAF’s mission, with the presence of trees being the principal component of an “evergreen agriculture” (World Agroforestry Centre, 2008). Within thearray of benefits broughtby trees, an important element is the positive effect of treeson soil properties and consequently benefits for crops. The presence of trees in farming systems, althoughan ancient practice, began to gain institutional attentionduring the 1970s and 1980s, with the beginning of studieson “agroforestry systems”.

While trees in general can provide a number of environmentalbenefits in both rural and urban landscapes, and playkey roles in ecosystem services provided by natural areas,in this paper we will restrict our focus to the effects oftrees on soil fertility, in the specific context of agriculturalsystems. Although the benefits that trees can provide onrural properties such as food security, household income,economic stability, and thermal comfort (shade) are mostoften associated with their products, such as fruit, timber,or other items, the inclusion of trees in agricultural systemscan also optimize nutrient cycling and have positive effectson soil chemical and physical properties. This process isespecially important in tropical soils, where a high degree ofweathering has created deep, leached soils that are poor inplant nutrients (Primavesi, 2001).In the humid tropics, the removal of surface litter ororganic matter generally results in the depletion of soilfertility in a few years (Ferreira *et al.*, 2006). In agricultural systemspracticed by traditional peoples, this

Fig. 2: Agroforestry system with rubber, cacao and acai showing the litter layer that is typically found in suchmultistrata systems (Rachel, 2012)

Fig. 3: Agroforestry system in initial phase, with black pepper as principal cash crop, interplanted with cupuacu and acai for futurefruit production, as well as timber trees as long-term products (Rachel, 2012)

limitation is circumventedby using the land for a short period (generally 2-3 years), after which the cultivated areas are left to fallowwith natural regeneration of secondary vegetation.

Ureolytic microorganisms and soil fertility:

Soil Micro-organisms play very active role in the decomposition of organic matter and are actively involved in the nitrogen cycles of various ecosystems. Different micro-organisms including filamentous fungi, yeasts, mycorrhiza, bacteria, cyanobacteria and actinomycetes possess the urease enzymes. Urease plays a role in soil enrichment through degradation or hydrolysis of organic nitrogen (N). Ureais an important fertilizer and may enter the soil with the excretions of higher animals and through destruction of the nitrogenous bases contained in the nucleic acids of plant and animal tissues. These products increase soil fertility by the action of urease. Ureolytic production and activity and fertility of soil are affected by chemical propertes of soil, environmental factors, sources of urea and soil micro-organism (Hasan, 2000).

Problem is encountered in use of urea as a fertilizer resulting fromits rapid hydrolysis to ammonium carbonate by soil urease activity and the concomitant rise in pH and accumulation of ammonium. These cause damage to germinating seedlings and young plants and gaseous lossof urea N as ammonia. Therefore technologies and management practices that improves urea efficiency and reduces its losses should be practised, These include coating ofgranules, soil incorporation and use of slow-release fertilizers. They form sparingly soluble urea-aldehyde compounds as ureaforms, crotonylidenediurea, isobutylidene diurea or using natural N-containing compounds suchas composted sludges of municipal and animal wastes. The degradative process of the ureolytic micro-organims on animal and plant organic N wastes could help to satisfy condition of eliminating excessive wastes and pollution and simultaneously supply plant with available N (Hasan, 2000).

The practices that can be used to improve urea efficiency and reduce losses include coating of granules, soil incorporation and addition of $CaCl_2$ (Hauck, 1984). Calcium salts delay urea hydrolysis and restrict the formation of unstable ammonium carbonate, which will decompose and release ammonia (NH_3^+). Where available and practiced for application, sewage sludge is often the most economical method of increasing soil fertility and improving its properties. It affects favourably microbial populations in the soil and their enzyme activity especially urease. Urease activity in soil increased with increased composted sludge of plants and animal wastes application and the inhibitory effect of salinity to urease activity was less severe in amendment soil (Hasan, 2000).

The essential non-renewable resource, soil with potentially rapid degradation rates and extremely slow formation and regeneration processes has to be maintained properly to avoid its degradation. The strategies discussed in this article such as integrated approach of maintaining soil fertility, proper use of ureolytic micro-organisms and agroforestry provides much scope in preventing the soil from degrading and maintaining soil fertility which leads to sustainable agriculture.

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