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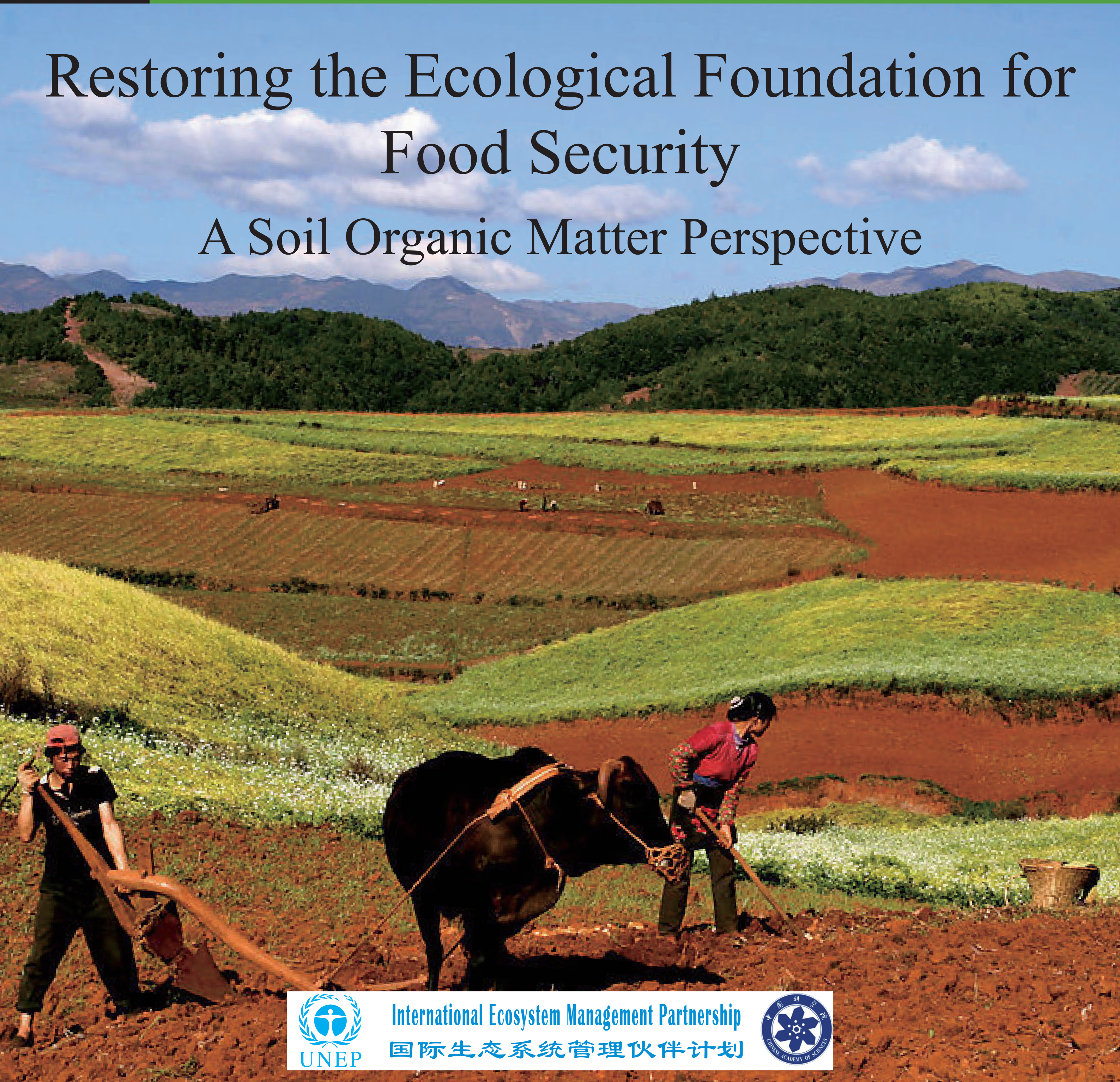
Restoring the Ecological Foundation for Food Security

A Soil Organic Matter Perspective



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International Ecosystem Management Partnership

国际生态系统管理伙伴计划

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Content

1. The Need for Sustainable Crop Production

More than 868 million out of the total world population of 7 billion people did not have access to sufficient food supply, and thus suffered from undernourishment in the period 2010-12.

Healthy and productive lives depend on food supply, yet the attainment of food security globally has not achieved as much progress as would be expected. More than 868 million out of the total world population of 7 billion people did not have access to sufficient food supply, and thus suffered from undernourishment in the period 2010-12 (FAO, 2012). The situation is still deteriorating as the world economic/debt crisis deepens, per capita food consumption increases and crop production stagnates in many food producers of the world (Foley et al. 2011). As the world population keeps growing, projected to reach nine billion by 2050, an increase in crop production of up to 40% of the present level will be needed (Rull 2010). Considering the increasing consumption of meat and high calorie food, social disparity, food waste and climate change impacts, this number could grow even larger by then, and exacerbates world food insecurity.

The world crop production has under through rapid increase since the 1960s, when the use of high-yielding crop varieties, fertilizers, biocides, irrigation, and mechanization were intensified at large scales across the world – mostly known as the "Green Revolution" (Matson et al. 1997). The Green Revolution was a major success in increasing crop production that outpaced global human population growth at least for some period (Rull 2010). In developing countries as a whole, crop production is reported to have increased by 118% between 1961 and 1990, with more than 90% of the contribution coming from yield increase rather than area expansion (Matson et al. 2012). Millions of people got rid of starvation across the world, especially in developing countries like India and China.

However, the increasing consumption of energy, biocides and fertilizers in agricultural intensification has undermined further increases in crop production and the health of the agro-ecosystems. At global scale, use of nitrogen fertilizers and crop yields have both increased in a nearly-linear fashion during the past 50 years (Cassman et al. 2003).However, the ability to sustain high crop yields per unit area of land despite high use of the fertilizers has become a major challenge (Matson et al. 1997). In fact, in recent years, crop yields are approaching biologically maximum level in many developed and some fast-growing developing countries (Cassman et al. 2003; Bommarco et al. 2012). At a global scale, in 24–39% of cereal (maize, rice, wheat and soybean)-growing areas, current crop yields either stagnated or declined during the last decade (Ray et al. 2012). In India, for instance, the intensive rice-wheat rotation system in the Punjab has shown signs of serious decline associated with loss of soil quality and increased plant health problems (Shiva 1991). Intensive use of fertilizers has interrupted normal soil nutrient cycle, and led to apparent soil degradation and heavy pollution in soil, water and air in many countries (Matson et al. 1997; Lal 2004; Khan & Hanjri 2009).

2. The Ecological Foundation of Crop Production

Agriculture supports over 90% of human beings for food supply (UNEP 2012). As part of the Green Revolution, modern agriculture has simplified traditional agricultural ecosystems and replaced biological functions originally provided by diverse communities of organisms, with increased external inputs of energy and nutrients (Bommarco et al. 2012). Crop's physiological and biochemical functions are well understood for human to control the growth of almost any crop. Nevertheless, for large quantities of crop production for the whole world, these techniques are still too costly and beyond the reach of most farmers in many developing countries. The importance of nature on agriculture is more fundamental, especially in developing countries where the use of modern technology is still relatively low.

The importance of nature on agriculture is more fundamental, especially in developing countries where the use of modern technology is still relatively low.

Ecosystem services lay the foundation for crop production (Bommarco et al. 2012; UNEP 2012). Among all natural bases and ecosystem processes influencing crop production, soil is one of the most valuable. Healthy soils improve air and water quality, increase land productivity, help resist the effects of drought and floods, improve energy efficiency and enhance the ability to mitigate climate change (Sorensen & Daukas 2010). Numerous other studies have demonstrated the importance of soil health on sustainable production of crops (Lal 2004; FAO 2006; Powlson et al. 2011; Mueller et al. 2012; Bindraban et al. 2012). The fundamental role of soil in agricultural production lies in nutrient provision. Soil also provides regulating services to hold water, sequester carbon, and provide habitats for plants or animals living in the vicinity. Furthermore, soils are normally treated as nutrient pools or buffer zones for plant growth because of their diverse composition, ubiquitous biochemical reactions, and the huge microorganism diversity. The nutrient buffer zones create environments that are suitable for roots, microbes and their interactions. The larger capacity the buffer zones are, the more stable the crops get nutrients and water, and the less probable they are under stressed condition, thus ensure higher crop production.

SOM dynamics is of vital importance to soil nutrient balance and soil health, but is largely overlooked

Even though important for crop production, soil is very fragile in nature. Misappropriate use of soil for crop production could result in reduced provision of nutrients, water, and regulatory capacity. In this regard, maintaining soil features in optimal conditions is essential for sustainable crop production. Therefore, conservation of a healthy status of the soil needs to be accorded top priority in national strategies.

3. SOM Dynamics and Crop Production

The return of nutrients to soil is crucial for the nutrient cycling in all terrestrial ecosystems. In traditional agriculture, this is done by keeping crop residues in the fields and applying organic manures to the soils. The soils can then support sustainably moderate yields without significant degradation, as in the cases in many traditional agricultural countries such as China (Miao et al. 2010; Pan et al. 2009). As one of the most important components of soil, SOM[1] plays an important role in ecosystem productivity, in the functioning of agro-ecosystem and in soil fertility (Tiessen et al. 1994; Loveland & Webb 2003; Pan et al. 2009). SOM affects both chemical and physical features of the soil, and is the focal point to soil life and the diverse functions provided by the range of soil organisms (FAO 2005; Kibblewhite et al. 2008).

SOM dynamics is of vital importance to soil nutrient balance and soil health, but is largely overlooked. The production-oriented agricultural intensification has led to over application of large amount of fertilizers, notably N fertilizers, across the world. The surplus nutrients are usually not taken up by plants and transformed to higher crop yields, but are either taken up by soil microorganism to actively decompose SOM, or lost in the environment. After several years, the

1 Soil organic matter (SOM) is normally defined as any material produced originally by living organisms that is returned to the soil and goes through the decomposition process (FAO, 2005).

SOM could be depleted, and large quantities of nitrogen (N) chemicals would remain in the soil, volatilize into the air, or washed to the water bodies, causing heavy pollution in soil, air and water bodies (Fig. 1). In some regions, the nitrogen fertilizer application rates have become so high that only 30% of the applied fertilizers can be utilized by crops. In China alone, more than 35-40% of the applied N is not taken up by crops, and is thus lost in the environment each year (Cheng et al. 2010). The depletion of SOM in over-fertilized soil as a result of agricultural intensification has already been reported around the world, including the USA (Matson et al. 1997; Fig. 2), China (Miao et al. 2010), India (Manna et al. 2004) and Africa (Cobo et al. 2010). In this regard, chemical fertilizers are no substitutes for soil organic matter, but rather need to be balanced with the later.

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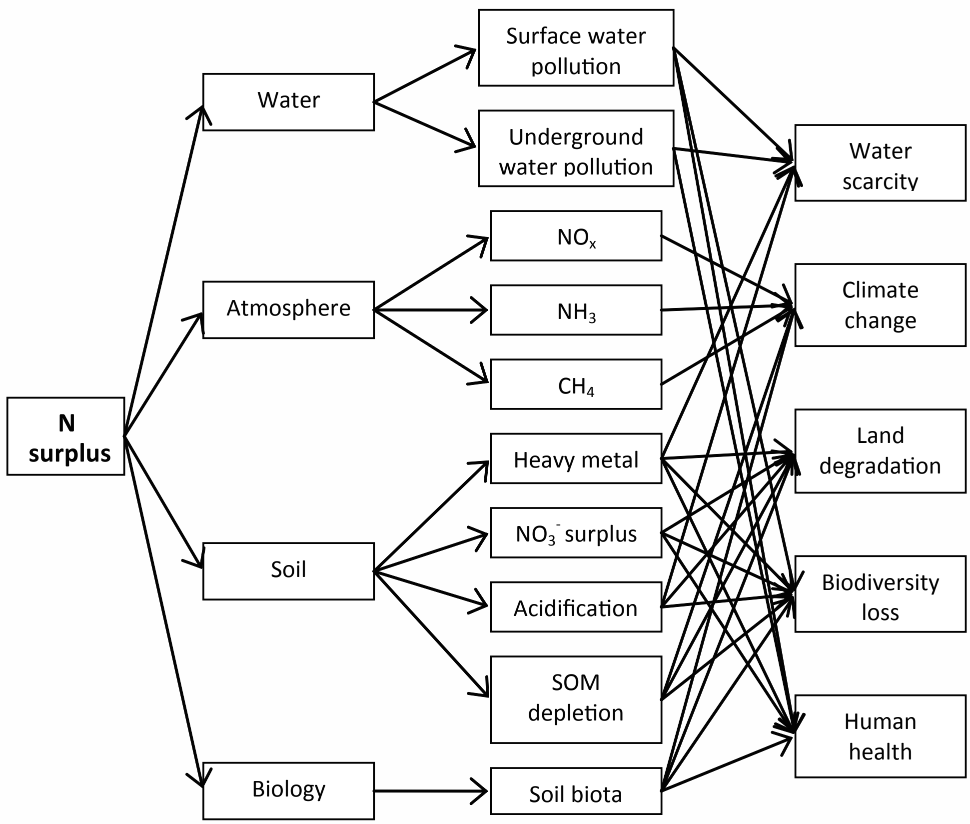

Fig. 1 The multifaceted and complex consequences of N surplus in agro-ecosystems. It is worth noting that N surplus is not the only driver of agro-ecosystem degradation. Other unsustainable practices, such as deep tillage and heavy application rate of biocides, could also add to specific consequences, and enhance soil degradation in the long run.

The role of SOM in crop production lies more on its buffering capacity when crops face short term unfavourable climatic or agronomic conditions, such as drought.

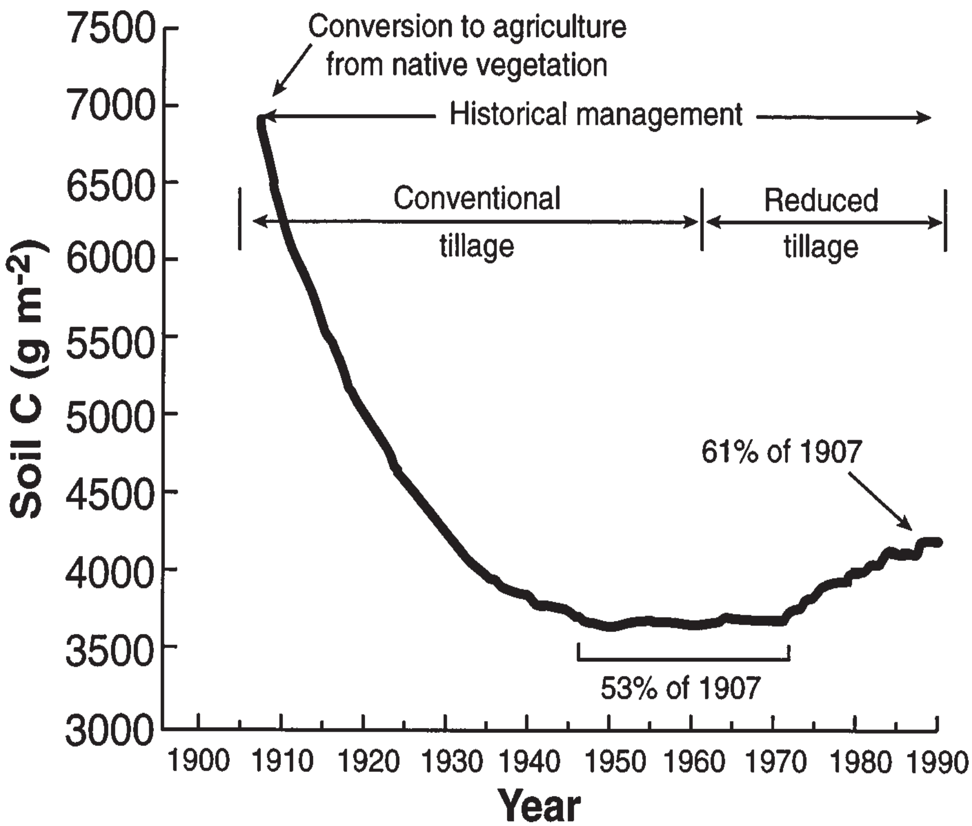

Fig. 2 Simulated total soil carbon (for soil depth of 0 to 20cm) changes for the central U.S. corn belt. Points at which soil carbon was 53 and 61% of concentration at conversion to agriculture (in 1907) are indicated (Adapted from Matson et al. 1997).

Whereas the relationship between SOM and crop yields varies from region to region and from time to time, it is certainly the case that the SOM contents and crop yields are positively correlated (Lal 2010; Seufert et al. 2012). The increments of crop production might not be proportionate with SOM content, but SOM will help to close the gaps of actual and potential yields, and achieve sustainable farming gradually (Lal 2004; Mueller et al. 2012). The role of SOM in crop production lies more on its buffering capacity when crops face short term unfavourable climatic or agronomic conditions, such as drought (FAO 2005).

Besides soil fertility enhancement, SOM could also improve soil structure and nutrient balance, harbour soil microorganism biodiversity, sequestrate CO_2, and improve agricultural environmental health (Lal 2004). Carbon sequestration, for example, plays a very important role in the global endeavour to stabilize and reduce GHG emission, mitigate climate change, and promote sustainable development (Dumanski 2004). It is worth noting that the effects of SOM on agricultural ecosystem and the rural regions are crosscutting and comprehensive, underling a bottom-up approach for food security, poverty eradication and climate change mitigation in the long run. The crop production based on improved SOM level will enhance agro-ecosystem functions and services, lead to a sustainable agriculture and make the implementation more beneficial if all of the co-benefits are taken into account (Fig. 3).

The crop production based on improved SOM level will enhance agro-ecosystem functions and services and lead to sustainable agriculture

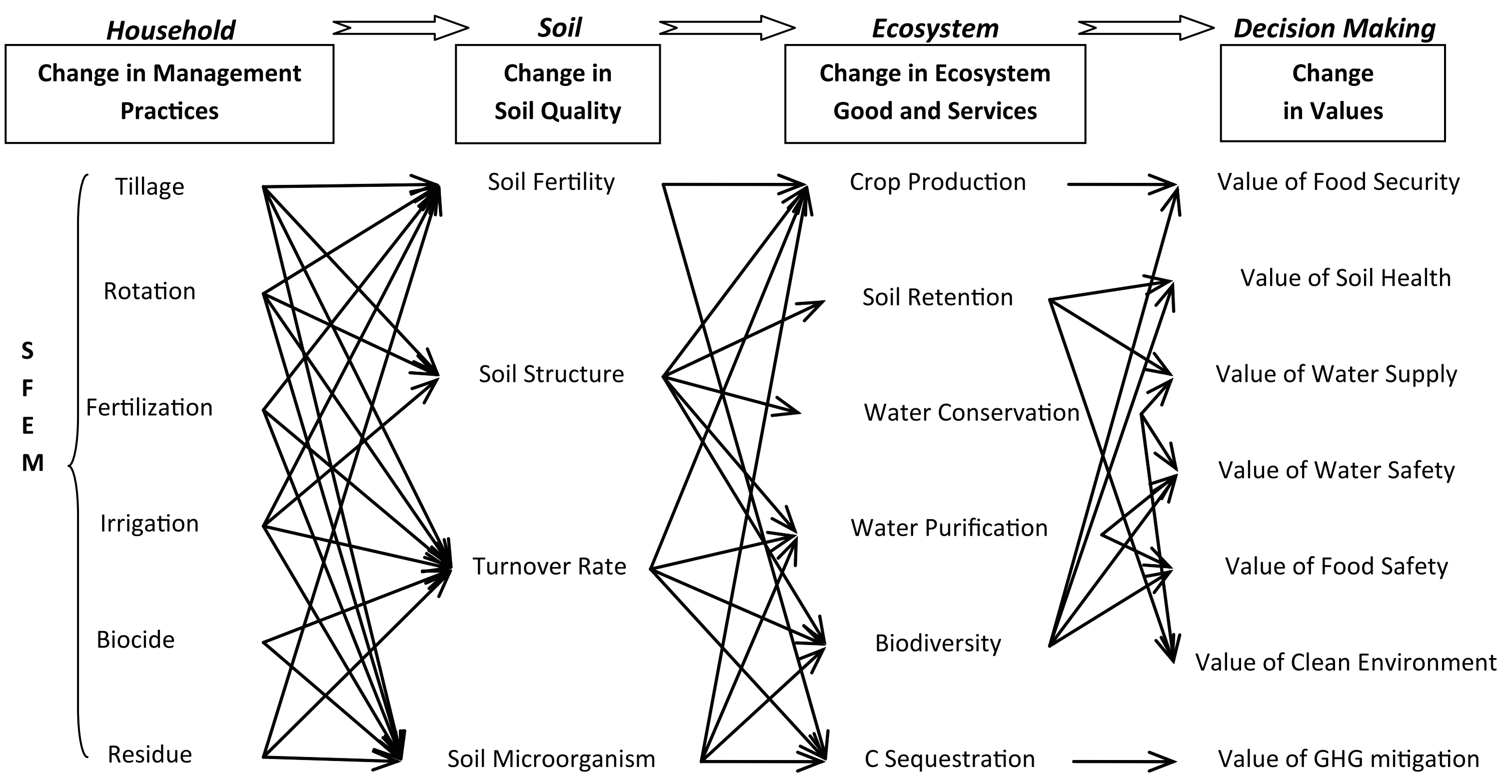

Fig. 3 A comprehensive and hierarchical framework of SOM Friendly Ecosystem Management (SFEM) and its linkage with soil, ecosystem, and their valuing for decision making. The SFEM will only succeed when all the aspects of the practices are handled properly.

4. SOM Friendly Ecosystem Management (SFEM) and Practices

SOM Friendly Ecosystem Management (SFEM) refers to practices based on ecosystem management theories and practices aiming at increasing SOM levels of the agricultural soil.

A sustainable agricultural production system is one with increased ecosystem values, taking productions, their environmental burdens and ecological services and products into consideration (Glendining et al. 2009). Management practices used in agriculture and forestry determine whether these lands are sources or sinks of carbon. Land under good conservation and nutrient management, conservation or zero tillage, well managed fallows, preservation of wetlands, etc, favour enhancement of carbon sinks at different scales.

SOM Friendly Ecosystem Management (SFEM) refers to practices based on ecosystem management theories and practices aiming at increasing SOM levels of the agricultural soil. SFEM attaches great importance on the theory and practices of ecosystem management, which was defined as "an integrated process to conserve and improve ecosystem health that sustains ecosystem services for human well-being" (Munang et al. 2011; UNEP 2009), indicating that the SFEM process should also be integrated, and aim at, conserving and improving ecosystem health.

Here we propose a portfolio framework which addresses the relevant issues. The solution needs to apply to different spatial scales (Tab. 1) and different stakeholders who might mobilize various managerial/policy measures and resources to enforce the effects. Conjunctions between different levels of stakeholders could also be in position for the sake of full implementation. In China, the high subsidies and tax reductions for fertilizer industry are now blamed for the over-fertilization in the agricultural regions across the country (Cheng et al. 2010). It is thus necessary that the state commission redirect the subsidies to some other agricultural items to encourage sustainable agricultural practices (e.g., organic farming or soil amendment).

Tab. 1 Category of SOM Friendly Ecosystem Management (SFEM) and its spatial scales.

Category	Spatial Scale			
	Ecosystem	Community	National	Global
Tillage	Minimize cultivation intensity; Increase land coverage; apply zero or reduced tillage; Increase mulch use; Decrease on-farm mechanization activities	Conserve fragile land by afforestation; Strengthen regional afforestation, Promote zero or reduced tillage and reduced mechanization at community level	Prevent deep tillage by legislation; Gradually remove subsides to mechanization; Subsidize farmers for conservative tillage; Abide to international conventions, such as UNCCD	Promote knowledge and technology transfers of conservative tillage among developing and developed countries
Rotation	Improve rotation of crops, especially with legume crops; Increase perennial crop rotation ratio	Coordinate and promote crop rotation; Conserve on-farm biodiversity	Encourage on-farm biodiversity conservation; Adjusting subsidize strategy to favour rotation; Regulate crop market to accommodate diverse crop products	Prevent trade protectionism; Promote free trade of crop products; Stabilize crop prices in developing countries
Fertilization	Avoid over fertilization; Increase fertilizer use efficiency; Balance fertilizer types; Use more (green) manures	Avoid over fertilization by monitoring nutrient status and prescribing site-specific fertilization plans	Shift subsidies from fertilizer industry to SFEM practices; Promote dissemination of scientific fertilization; Setup guidance and incentives for proper fertilization	Promote knowledge and technology transfers of fertilization for developing countries; Support fertilizer industry and improve fertilization use capacity and efficiency in developing countries
Irrigation	Reduce flood irrigation; Enhance irrigation efficiency; Reinforce water recycling	Improve irrigation facilities and infrastructures for more efficient management of water; Reduce groundwater extraction	Promote dissemination of efficient and scientific irrigation; Subsidize on agricultural irrigation improvement	Integrative management of international rivers; Conserve head water regions; Enhance knowledge and technology exchange and transfer of scientific irrigation among countries
Residue	Stop burning of crop residues; Enhance residue use for energy and nutrients; Utilize forage by grazing rather than by harvesting	Develop husbandry to balance the C in residues; Promote residue treatment and return in community level	Prohibit burning of residues; Setup incentives for the farmers to either leave the residues or to return them after treatments	Encourage exploitation and technology transfer of alternative energy; Prohibit the development of unsustainable bio-energy
Biocide	Reduce biocide application rates; Increase their use efficiency; Develop integrated pest/herb management	Promote integrated pest/herb management; Employ biological control over chemical control; Regulate and standardize application techniques of biocides	Regulate production of toxic biocides; Promote dissemination of scientific application; Strengthen alien species management; Abide to international conventions, such as UNCBD	Prohibit proliferation of toxic biocides in developing countries; Enhance knowledge and technology exchange and transfer of biological control of pest/herb

... only if all these aspects are addressed properly across the different spatial and temporal scales can the agricultural production be transformed into sustainable processes

The portfolio framework considers the following aspects: tillage, rotation, fertilization, irrigation, residue and biocide (Fig. 3; Tab. 1). The six aspects cover key issues of crop production, such as management of soil, water and crops, fertilization, and application of biocides. Even though categorized, these aspects are interdependent and could contribute to one another upon wise management. For example, rotation with different crop types improves soil nutrient balance and structure, but it's also a good practice to reduce pest incidence, and thus could cut down biocide use, improve soil microorganism activity and soil turnover rate, thus enhance soil nutrient, reduce fertilizer use and increase SOM contents (Fig. 3).

In SFEM, the practices that deal with the six aspects of agricultural production are basically consistent with many other research work, e.g., organic farming, conservation farming, sustainable intensification, ecological intensification, etc. Actually, SFEM is not exclusive to the practices that have been quite documented in these approaches as well as practices that will be based on these theories. We argue that only if all these aspects are addressed properly across the different spatial and temporal scales can the agricultural production be transformed into sustainable processes, with increased SOM content to support increasing demand of crop production. Otherwise, agricultural ecosystems might collapse once soil fertility is completely depleted and agricultural environment and resources damaged, even if a large amount of inputs were applied.

As the Chinese rice breeding scientist Prof. Longping Yuan stated, "Good seeds, good soil and good management are all required for high yields". As we have high-yield seeds available across many parts of the world, high yields will be within reach if good soil nutrient condition and good management are adopted. The SFEM in this study, rather than undermining the crop yields because of reduced use of chemicals, is actually contributing to the crop production in the long run, owing to enriched soil nutrient cycling and other ecosystem services that come with the practices.

5. Policy Implications

As suggested in other researches, the ability of a farmer to close the yield gaps ultimately depends on either increased conventional intensification with known negative environmental impacts or, alternatively, the integrity and extent of several natural supporting and regulating services, such as SOM enhancement (Bommarco et al. 2012). In order for the various stakeholders to participate actively in SFEM, certain policies need to be in place in a way to promote the conservation and restoration of soil or, specifically, SOM in agricultural practices. Fiscal incentives can be a central theme of the national strategies and policies, with the first and foremost incentive to encourage farmers to shift their focus from short-term crop yields to long-term soil health. To achieve this, subsidies could be redirected from applying chemical fertilizers to employing SFEM practices (Tab. 1). Small scale pilot projects or demonstrations need to be established before full implementation in large scale. Site-specific regulations could then be setup based on these trials to guide the implementation and certification of SFEM and allocation of governmental subsidies.

Fiscal incentives can be a central theme of the national strategies and policies to encourage farmers to shift their focus from short-term crop yields to long-term soil health.

Many nations already recognized the need for the shift, and started to take actions. In India, the vicious effects of chemical fertilizers on food security and environmental health have already been acknowledged by the government, and the old fertilizer policy that subsidizes fertilizer production has been replaced with a Nutrient Based Subsidy (NBS) system for fertilizers (Mishra & Gopikrishna 2010). Practices such as soil test based, cropping system specific fertilizer uses in conjunction with organic and bio-fertilizers were also proposed by the government in order "to eliminate the fertilizer use anomaly, arrest soil degradation due to imbalance use of chemical fertilizers and to ensure sustainable production with good soil health"[2] .

In the "Green for Grain" (G4G) project implemented in China, agricultural fields that are either low in production or fragile in ecosystem are provided with subsidies to plant trees or grasses in a way to combat deforestation,

2 Government of India, Economic survey 2007-08, Ministry of Finance, p. 20, para 1.65. Also see: B.C. Roy, G.N. Chattopadhyay, Subsidising food crisis: synthetic fertilizers lead to poor soil and less food, Greenpeace India, 2009; and R. Tirado, Chemcial fertilizers in our water: an analysis of nitrates in the groundwater in Punjab, Greenpeace India, 2009

ecological degradation and over cultivation of slopping land and soil erosion. Instead of jeopardizing the food security due to decrease in farm land, the project actually enhanced the food security as a result of combined effects of increased ecosystem integration, retained soil erosion, and improved household's incomes and livelihood (Liu & Wu 2010).

Investments are needed for large scale field survey, development and application of in situ measuring techniques, and exploration of possible surrogates.

Even though the shift to SFEM crop production shows a lot promises, it isn't without any trouble. Right now, three challenges can be seen from implementing the shift and need to be addressed.

Firstly, capacity for the monitoring of SOM status and impacts is lagging behind in most developing countries. This capacity gap makes it difficult to evaluate the effects of the new practices with conventional agricultural practices. Since crop yields are more straightforward to measure, farmers would respond and adjust their practices if the effects of the shift are quick and beneficiary. To overcome this challenge, investments are needed for large scale field survey, development and application of in situ measuring techniques, and exploration of possible surrogates. The ongoing World Soil Information programme of the International Soil Reference and Information Centre (ISRIC)[3] will establish a baseline for many developing countries across Asia and Africa which don't have any related information yet. However, small scale survey and monitoring are still in great demands for pilot projects and demos. In this case, technology transfer and investments between the global North and the South and among the South could be of great help.

Secondly, concerns over decreased crop yields might impede the shift to SFEM if farmers stick to their original habits and opinions. The positive relationship between, for example, high input of fertilizers or deep tillage and high crop yields in conventional agriculture has been taken as granted by a majority of farmers and government officials who might refuse to shift to SFEM when fewer fertilizers or reduced tillage are prescribed. Specific insurances can be offered, by agricultural associations or companies entrusted by government agencies, to farmers implementing SFEM practices so as to take the risk out for the farmers, and build confidence for the practices. It is also necessary that proper scientific research, dissemination and demos based on existing scientific evidences be carried out before promoting the shift. The pros and cons of the shift have to be explained to farmers and government officials before the

3 http://isric.org/

trial, and precise calculation could be performed to decide the tradeoffs. This will help the farmers to try the alternative practices and carry out sustainable farming. Theoretical and methodological advances in ecological economics that help to facilitate the evaluation and tradeoffs work might also contribute to solving the problem in the near future.

Thirdly, the shift might require more managerial and labour input, which is less favourable in places where brain drain and labour drain are becoming more severe under rapid urbanization processes. Rural areas are facing the big challenge of lacking sufficient labour forces to carry out basic agricultural activities especially where mechanization rate is still low. It's widely accepted that improving farmers' income, livelihood and social status could attract more people to stay in the rural regions. Governments could leverage more taxes from agriculture and increase subsidy levels to improve the farmers' income level. Their livelihood and wellbeing can then be improved by investing in health and educational facilities in rural regions.

Governments could leverage more taxes from agriculture and increase subsidy levels to improve the farmers' income level.

There are also discussions that food security challenges potentially can be addressed through a variety of other approaches including, for example, new breeding technologies (Tester & Langridge 2010), the development of genetically modified (GM) crops, new kinds of integrative crop-livestock systems and precision agriculture (adapting production inputs site-specifically within a field by using both "high tech" remote sensing and computer-based mechanized approaches) (Gebbers & Adamchuk 2010). However, without good care of the soil health, these technologies won't add values. In a word, a solid ecological foundation needs to be laid for a sound food security, and from a sustainable point of view, every effort needs to set this as the final target and criteria.

6. Conclusions

The study achieved the following conclusions:

- The global food security is facing serious challenges due to the stagnating crop production in many countries as well as the aggravating agro-ecosystem degradation caused by unsustainable farming practices and economic activities. The world is in a great need for a sustainable crop production that fulfils the human demand while without encroaching further the ecological foundation of the agricultural production at the same time.

- SOM provides a direct reference and platform with which the crop production, agricultural sustainability and the environmental externalities can be addressed. With SOM, soil nutrient and land management are closely correlated, and sustainable production could be achieved under the same framework.

- SFEM hold great premises for improving food security while enhancing its ecological foundation and agriculture environmental sustainability. Six categories are suggested in the context to address the SOM issue in a holistic way. An immediate shift to SOM Friendly crop production will ensure a secure food production, if appropriate SFEM practices were performed.

- Policies and actions could be put forward to promote the conservation and restoration of soil or, specifically, SOM in agricultural practices. Even though challenges remain for the shift to take place, the perspective is still prosperous and would play its role in the near future.

- The approach in this study is basically not distinct with many others agricultural approaches quite popular in the science communities, but with different motives and criteria. A variety of other modern approaches can also add values to addressing the issue.

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