INTERNATIONAL
SOIL AND WATER
CONSERVATION RESEARCH

Global achievements in sustainable land management

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Abstract

Identification and development of sustainable land management is urgently required because of widespread resource degradation from poor land use practices. In addition, the world will need to increase food production to meet the nutritional needs of a growing global population without major environmental degradation. Ongoing climate change and its impacts on the environment is an additional factor to consider in identifying and developing sustainable land use practices. The objectives of this paper are to: (1) provide a background to the need for sustainable land management, (2) identify some of its major components, and (3) discuss some examples of sustainable land management systems that are being practiced around the world. Some common components of this type of management are: (1) understanding the ecology of land management, (2) maintenance or enhancement of land productivity, (3) maintenance of soil quality, (4) increased diversity for higher stability and resilience, (5) provision of economic and ecosystem service benefits for communities, and (6) social acceptability. Several examples of sustainable land management systems are discussed to illustrate the wide range of systems that have been developed around the world including agroforestry, conservation agriculture, and precision agricultural systems. Improved technology, allowing for greater environmental measurement and for improved access and sharing of information, provides opportunities to identify and develop more sustainable land management practices and systems for the future.

Key Words: Soil degradation, Ecosystem services, Diversity, Soil quality, Agroforestry, Conservation agriculture, Precision agriculture

1 Introduction

Sustainable Land Management (SLM) has been defined as "a knowledge-based procedure that helps to integrate land, water, biodiversity, and environmental management to meet rising food and fiber demands while sustaining ecosystem services and livelihoods" (World Bank, 2006). Smyth and Dumanski (1993) defined SLM as a combination of technologies, policies, and activities aimed at integrating socioeconomic principles with environmental concerns in order to maintain and enhance productivity, reduce the level of production risk, and enhance soil's capacity to buffer against degradation processes, protect the potential of natural resources and prevent degradation of soil and water quality, be economically viable, be socially acceptable, and assure community access to the benefits from improved land management. A definition developed at the 1992 Earth Summit identifies SLM as "the use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions". SLM encompasses other established approaches such as soil and water conservation, conservation agriculture, natural resources management, and integrated ecosystem management. It promotes integration of social, economic, physical and biological needs and values, to achieve a more holistic, productive, and

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healthy ecosystem. Land management itself could be considered "a planned intervention into natural processes in order to assure predictable outcomes of benefits to the health and welfare of humans" and is often guided by sociological factors(Lassoie and Buck,2000).

SLM will be imperative for the world to face the multiple challenges it will need to address currently and in the future. Among these major challenges is the need to increase food production to meet the nutritional needs of a growing world population without serious degradation to the environment. With the world's population expected to reach 9.2 billion by 2050, one estimate is that food production will need to increase by 50% by 2013 and double in 30 years(Glenn et al.,2008). The need for meeting food demand is made more urgent by the fact that in 2009 over 1 billion people worldwide were undernourished and this number has been increasing over the last 20 years (FAO,2009). In the past, increases in world food demand have been met by increasing the agricultural land area, improving plant genetics and intensifying input use(e.g., fertilizers and pesticides), but in the future, the needed increased agricultural intensification may result in further global environmental degradation if more sustainable agricultural practices are not widely adopted(Tilman et al.,2002).

Land degradation is a global problem and can be brought about by numerous ways such as overreliance on monocropping, excessive tillage, overgrazing, deforestation, and poor management of agricultural chemicals and fertilizers. Increased agricultural intensification has caused a rapid increase in the number of hypoxic zones in the world's coastal waters from an estimated 44 in 1995 to 169 in 2008(Selman et al.,2008).

The primary anthropogenic source of nitrous oxide, a major greenhouse and ozone-depleting gas, is agricultural soil management, which accounted for 60 percent of the nitrous oxide emissions reported in 2005(Smith et al., 2007). From 2005 to 2030, nitrous oxide emissions from agricultural soils are projected to increase by 34 percent (EPA,2011). The primary reason for the increase in nitrous oxide emissions is the expected rise in crop and livestock production, with expanded use of synthetic fertilizers, to meet the growing fertilizer consumption requirements of developing countries in Asia, Central and South America, and Africa(EPA,2011).

The number and amount of xenobiotic compounds considered harmful to human, plants, and animals have been increasing steadily in production agriculture. Although synthetic chemicals are an integral part of modern agriculture, serious negative impacts have been reported because of accumulation of these chemicals in the environment(Allran and Karasov,2000). Environmental exposure to agrochemicals, such as herbicides, can occur at various locations and may include manufacturing sites, loading sites, and application sites(Allard and Neilson,1997).

Development of sustainable land use practices and systems are urgently required because of widespread resource degradation from poor land use practices. For example, almost 75 percent of Central America's, 45 percent of South America's and 11 percent of Asia's agricultural land have been seriously degraded(Scherr,1999). Three-quarters of Africa's farmland has severe soil degradation caused by wind and soil erosion and loss of mineral nutrients(Henao and Bannante,2006). The loss of potential productivity due to land degradation(soil erosion) worldwide is estimated to be equivalent to some 20 million tons of grain per year(UNEP,1999). Soil degradation may result in increased poverty and severe environmental problems(e.g., decreased biodiversity and water quality) (Eswaran et al.,1997). Examples of soil degradation include loss of soil organic matter, a decline in soil fertility and soil structure, increased erosion, salinity, acidity or alkalinity and the effects of toxic chemicals, pollutants or excessive flooding(Lal et al.,1998).

Soil degradation can be accelerated or mitigated by several factors including soil resilience, landscape factors, management practices and climate(Lal et al.,1998). The impacts of climate change which include increases in temperature and a higher frequency of extreme weather events, on soil quality will not be uniform across all agricultural regions and are predicted have more severe negative implications for food production in food-insecure countries(Parry et al.,2004; Fuhrer,2003). Ongoing climate change and its impacts on the environment is an additional factor to consider in identifying and developing sustainable land use practices.

The objectives of this paper are to: (1) provide a background to the need for SLM, (2) identify some of its major components, and (3) discuss some examples of SLM systems that are being practiced around the world. The additional goals of this paper are to highlight the lessons learned and global achievements that identification and development of these sustainable practices represent and to suggest that increased research and technological advancements may provide many opportunities for future improvements in land management.

2 Components of SLM

Extensive research has been conducted to identify and develop SLM practices and systems for a wide range of environments and socioeconomic conditions that exist across the world. This research suggests that while there is great diversity among these systems, there are also several common components of these systems. Among these common components are: (1) understanding the ecology of land use management, (2) maintain or enhance productivity, (3) maintenance of soil quality, (4) increased diversity for higher stability and resilience, (5) provision of economic and ecosystem service benefits for communities, and (6) social acceptability.

2.1 *Understanding the ecology of land use management*

Sustainable land management requires a better understanding of direct and indirect effects of land management on ecosystem functions. An example of an ecological assessment in agroecosystems was presented by Motavalli et al. (2004) in examining the direct and indirect effects of the introduction of transgenic crops into agroecosystems on soil properties and processes (Fig. 1). The direct effects may include changes in root exudates with possible effects on the rhizosphere, gene transfer from plant materials into soil microbes and the effects of possible changes in management practices, such as with pesticide applications, fertilization or tillage. The indirect effects of the transgenic crop includes changes in the quantity and composition of crop residues, changes in animal and agricultural processing wastes, effects on soil erosion and runoff and the possible increased use of marginal lands. Subsequent research by Mungai et al. (2005) investigated the effects of planting Bt corn on crop residue composition and decomposition for both the initial corn crop and the subsequent soybean crop in the rotation.

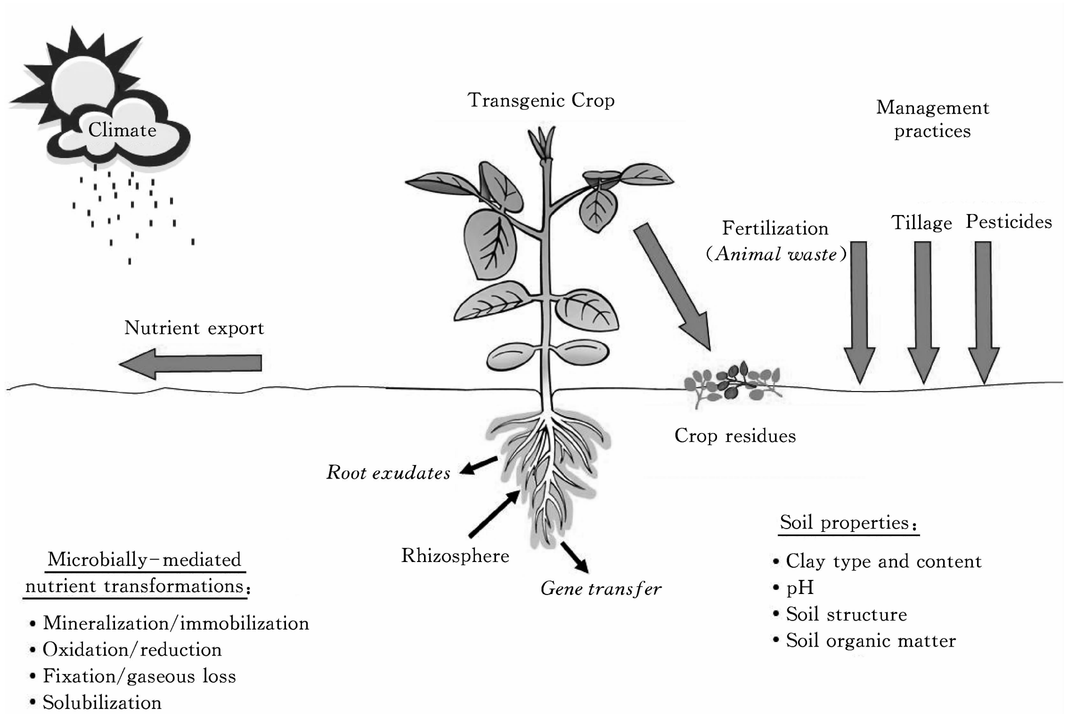

Fig. 1 The possible direct and indirect effects of the introduction of transgenic crops on soil properties and processes (Motavalli et al., 2004)

Similarly, greater appreciation of the effects of individual field management on watersheds and other ecosystems at different scales has also contributed to a better evaluation of SLM. Unfortunately, still very little is known regarding ecological interactions in major agroecosystems and landscapes and the effects on ecosystem services associated with agriculture (Robertson and Swinton, 2005).

2.2 *Maintain or enhance productivity*

While world population is expected to reach approximately 9.2 billion by the end of year 2050, agricultural productivity has to be doubled to meet the rising need of food crops. Every year approximately 13 million ha of land is converted to agriculture primarily from forest (FAO, 2002). Yet it is envisioned that producing enough food for all people in the world in the future would be a great challenge. Although global land productivity per unit area increased by around 2.4 times in 2005 than what it was in 1961, most of that increase occurred in the years from 1961 to 1990, after which the rate of productivity increase slowed down (Fig. 2) by a large proportion (Alston et al., 2009). To achieve a SLM system, it will be critical to prevent environmental degradation while optimising productivity.

However, Robertson and Swinton (2005) pointed out that current management practices are devoid of ecosystem sustainability approaches and thus the environment could become vulnerable under the immense pressure of higher food production. Since productivity is ultimately linked to the ecological productivity or net primary productivity, extensive research investigating the interaction between agricultural crops with their biotic and abiotic environment would be crucial for developing SLM systems while maintaining or enhancing productivity.

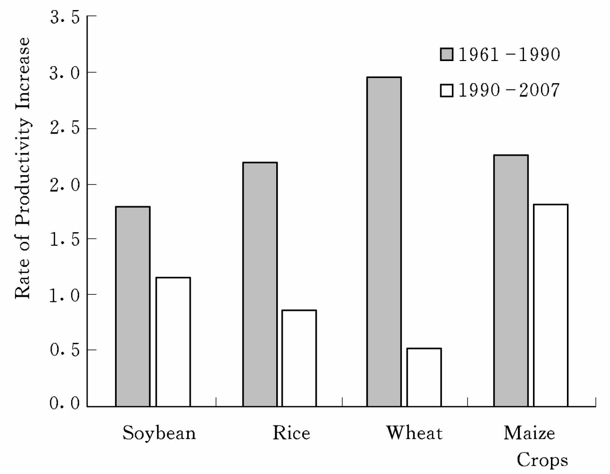

Fig. 2 Slowing rate of productivity in the last two decades compared to the previous three decades (Adapted from Alston et al., 2009)

2.3 *Maintenance of soil quality*

Soil quality has been defined as "the capacity 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). The soil resource provides multiple functions or ecosystem services including nutrient cycling, maintenance of water relations, biodiversity and habitat, filtering and buffering and physical stability and support (NRCS, 2011). Soil quality is an assessment of the soil's capacity to support a particular function, such as serving as a medium for plant growth, and, therefore maintenance of soil quality is an important component of SLM.

A significant achievement for use of the soil quality concept as a management tool has been the establishment of a process for identifying appropriate biological, chemical, and physical indicators for assessing soil quality, development of scoring functions for interpreting the results from the indicators, and the increased availability of indices for integrating the results into a single understandable result (Andrews et al., 2004). Examples of these soil quality indices include the simple multiplicative index proposed by Doran and Parkin (1994), the soil management assessment framework put forth by Andrews et al. (2004) (Fig. 3) and the Cornell Soil Health Test described by Gugino et al. (2009).

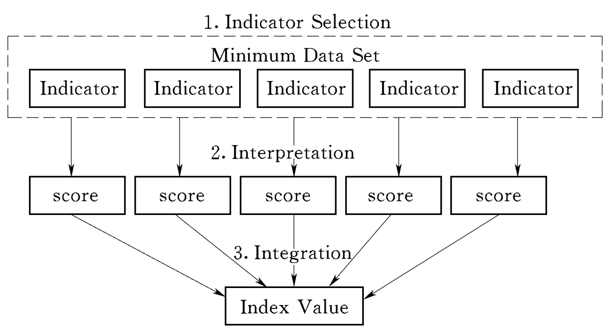

Fig. 3 Flow chart for assessing soil quality (Andrews et al., 2004)

A major constraint for use of soil quality assessment as a tool for sustainable land use management has been the high cost involved in traditional soil testing, the inaccessibility of soil testing facilities for land owners in developing countries, and the relative lack of interpretation information and recommendations based on the results of the soil test information. Development of rapid and low-cost soil quality assessment procedures, accompanying training programs, and research-based recommendations are urgently required.

2.4 *Diversity for increased stability and resilience*

Intensive agriculture usually involves mono-cropping, heavy tillage, high inputs of fertilizers, pesticides and herbicides which may lead to ground water contamination, erosion, reduced biodiversity (Aude et al., 2003) and degradation of soil and land resources. Modern agriculture with intensified farming practices has caused loss of biodiversity around the world resulting in vulnerable ecosystems (Matson et al., 1997; Tilman et al., 2001). Diverse ecosystems are generally considered more constant, reliable, predictable, and less prone to change or invasion than simple systems (Downing et al., 2012). Some examples of increased diversity in agroecosystems include crop rotation, inclusion of cover crops, intercropping, agroforestry managed fallow and polyculture. These practices often reduce diseases and pests, increase production and income stability and possibly buffer against disturbances, such as climate change (Lin, 2011).

One example of the importance of diversity for sustainable land use management has been in the Andean high plateau (Altiplano) region, which is one of the poorest regions in the world with a high vulnerability for extreme climate events (e.g., hail, drought, frost) affecting crop production (Quiroz et al., 2006; Gilles and Valdivia, 2009). Indigenous farmers in this region reduce risk to maintain stable production by planting multiple cultivars of potato and quinoa (*Chenopodium quinoa* Willd) in one field. This practice insures stable production in the event of poor weather or the onset of pests and diseases since at least one cultivar may be resistant.

Another example of the importance of diversity is with soil microbial communities. These communities play a very important role in ecosystem nutrient cycling (Wardle and Giller, 1997) and indirectly in crop production. Van der Heijden et al. (1998) demonstrated that mycorrhizal diversity directly affected plant diversity and production. Soil health is one of the important criteria for SLM systems and soil health has been associated directly with soil microbial diversity. Torsvik et al. (1990) showed that while the unit of microbial diversity can be up to 11, 500 in a pristine sediment, the diversity gradually decreases with increased perturbation and can be only about 350 in a methane amended agricultural soil. Griffiths et al. (2000) showed through empirical observation the clear relationship between microbial diversity and ecosystem functions. Available research findings indicate that higher microbial diversity can be directly proportional to the soil health and by extension for sustainable land management.

2.5 *Economic and ecosystem service benefits for communities*

The concept of ecosystem services has been defined as "the benefits people obtain from ecosystems" and includes a range of services such as provisioning services, regulating services, supporting services, and cultural services (Millennium Ecosystem Assessment, 2005). These services have a strong linkage with human well-being, but have not always been calculated in economic assessments of different land management practices or systems. In addition, improvements in SLM and livelihoods often results in improved protection of natural ecosystems and the ecosystem services offered by those ecosystems (Fig. 4).

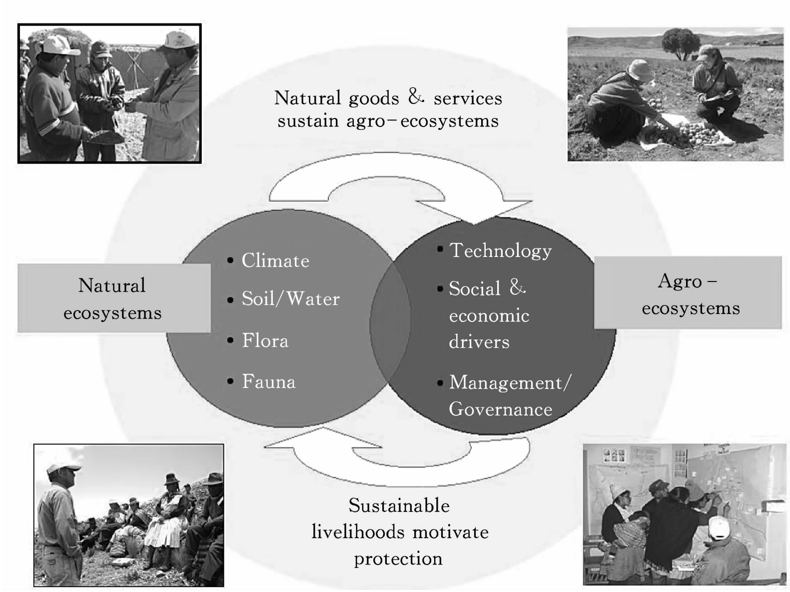

Fig. 4 An integrated ecosystem perspective between natural and managed ecosystems (Adapted from Per Rydén, 2010)

An achievement in the identification and development of SLM has been the increased awareness of the importance of insuring both short- and long-term economic and ecosystem benefits for communities who are involved in the land management. Moreover, the land use practices should be identified and developed with the involvement of the communities so that the practices are appropriate for the local socioeconomic and cultural conditions and, therefore, would become more rapidly adopted by the community.

2.6 *Social acceptability*

The foundation for success of any SLM system often depends on the adaptability and the social acceptability of that system by the affected communities. Sustainability among different communities may have different levels of social perception. Various factors such as knowledge and education, geographic variability (Brunson and Steel, 1996), time (Bengston et al., 1998), and social affiliation (Steel et al., 1998) may affect social acceptability. While the primary goal of investigating social acceptability is to implement SLM systems, consideration needs to be given to the variability among stakeholders in terms of need, perception, and demand.

3 Examples of sustainable land use systems

Several examples of sustainable land use systems exist around the world and each example contains more than one of the components previously discussed in this paper. The examples included in this discussion have been selected to illustrate the wide range of systems that have been developed or are in the process of being developed. They also show the opportunities for further research, development and outreach and education.

3.1 *Agroforestry systems*

Agroforestry systems have been defined as "intensive land management that optimizes the benefits (i. e., physical, biological, ecological, economic, and social) from biophysical interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock" (Gold et al., 2000). The major categories of agroforestry practices are: (1) alley cropping, (2) buffers, (3) forest farming, (4) windbreaks, and (5) silvopasture. These practices are widespread in the tropical regions but have not been extensively adopted in temperate regions.

Vegetable agroforestry (VAF) practices have been extensively studied in the upland areas of the Philippines and other Asian countries (Reyes, 2008). Placement of trees as contour hedges with vegetable production has been observed to reduce soil erosion, increase fertilizer use efficiency, increase incomes of smallholder farmers, and improve soil carbon sequestration (Mercado et al., 2009). Competition among tree and vegetable crops was addressed by investigating optimum tree spacing and selecting suitable tree and vegetable species within the VAF practice (Fig. 5).

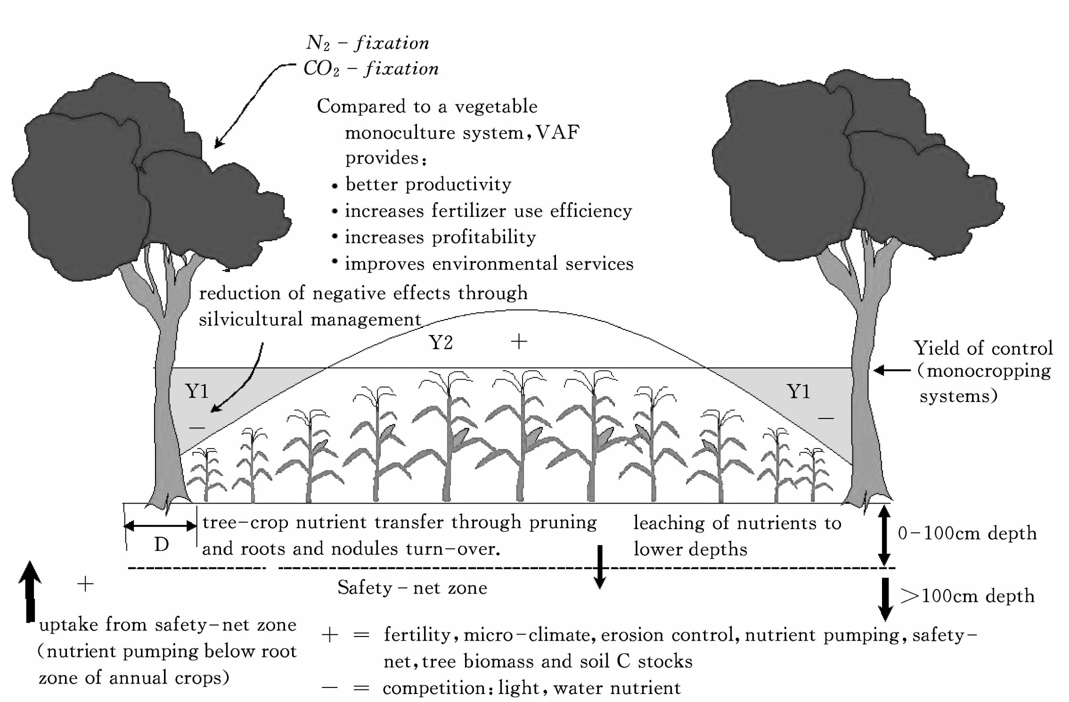

Fig. 5 The VAF practiced in the upland areas of the Philippines (Mercado, 2009)

3.2 *Conservation Agriculture*

Conservation Agricultural (CA) systems are being extensively researched around the world and show promise as a SLM system (Hobbs et al., 2008). The principles of CA include: (1) minimum mechanical soil disturbance (e.g., conservation tillage and direct seeding), (2) permanent organic soil cover (e.g., residues, cover crops), and (3) diversification of crop species grown in sequences and/or as associations (e.g., crop rotation) (FAO, 2012). Interest in this system in several regions of the world has been in response to increasing resource degradation and declining crop yields that has been observed with conventional land use practices.

A review of research studies examining farmer adoption of CA indicate that highly localized social, economic and environmental factors affect adoption (Knowler and Bradshaw, 2007) and, therefore, local on-farm research involving community participation may be a successful approach to promote adoption of CA. Some issues with adoption of CA have included competing uses for crop residues (e.g., livestock feed), increased labor requirements, the difficulty of direct seeding without appropriate equipment, and initial increased weed problems and lower yields (Giller et al., 2009).

3.3 *Precision agricultural systems*

Precision farming has been defined as "an information and technology-based farm management system to identify, analyse and manage variability within fields for optimum profitability, sustainability and protection of the land resource" (Roberts et al., 1994). It has also been called site-specific farming or prescription farming, and can range from simple practices, such as field scouting or spot application of pesticides, to more complex land management practices that utilize Global Positioning System (GPS)-based technology (McLoud et al., 2007). Precision agricultural practices include yield monitoring and mapping, grid sampling, sensor-based mapping and remote sensing, and several variable rate application methods such as variable rate fertilizer application. The precision agricultural systems generally provide more in-season information for improved farmer decision-making and identify spatial variability among soils and plants due to differences across agricultural landscapes.

More recently, Motavalli et al. (2012) have developed a variable source fertilizer strategy for corn production that utilizes multiple sources of fertilizer (e.g., enhanced efficiency nitrogen fertilizers, urea) for application to a single field based on maps of areas of low and high potential environmental nitrogen loss (Fig. 6). This practice has been shown to increase overall productivity and reduce environmental N loss. It also illustrates the use of new technology to provide additional information that can improve land use management by better identifying spatial variability in fields across agricultural landscapes and by identifying areas of greater potential environmental sensitivity within those landscapes.

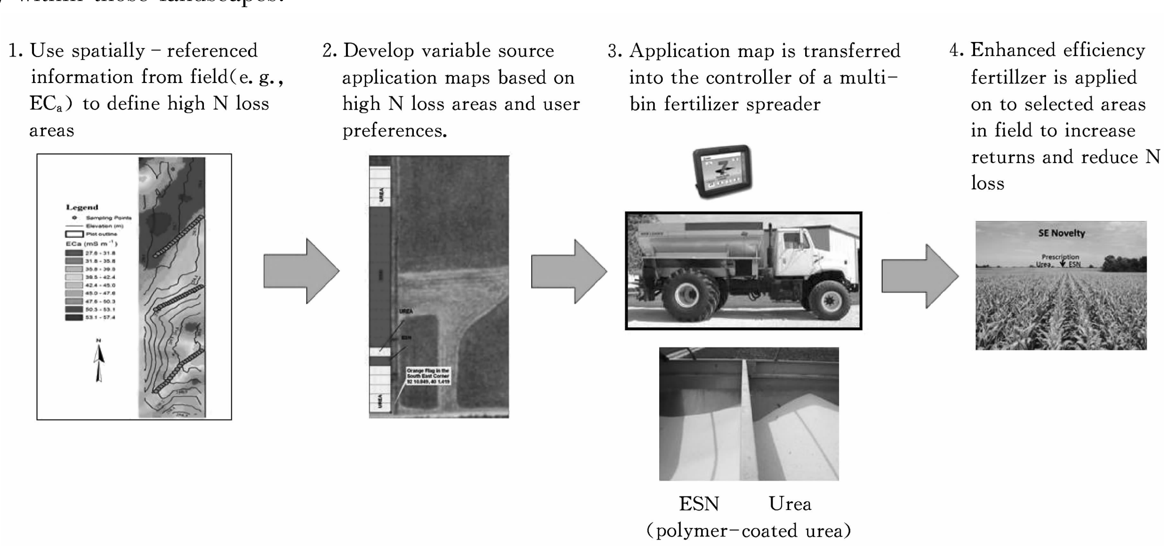

Fig. 6 Steps in variable source fertilizer management using urea and enhanced efficiency nitrogen fertilizers (e.g., polymer-coated urea)

4 Conclusions

A major challenge facing the world today is to increase food production to meet the needs of a growing global population without a major negative impact on the environment and while climate change is occurring. Many examples of sustainable land use management have been developed over the centuries by the world's farmers and landowners and through scientific research. Some principal components of these land use practices have been to understand the ecology of land use management, maintain or enhance productivity, maintain soil quality and plant diversity, and insure the practices are socially acceptable and provide sufficient economic and ecosystem benefits for communities.

Improved technology recently being developed provides opportunities to develop more sustainable land management that will provide better information to the land owner for decision-making through guidelines in selecting suitable crops, best management practices, and other cultural practices for his land. Such information should take into account various scales (e. g. plot, watershed, region) and should be readily available through public and private extension services at the disposal of the stakeholders. Future research should focus on interdisciplinary approaches that involve scientific, economic, and social components along with local and regional knowledge systems.

Acknowledgements

This paper was originally presented at the Scientific Workshop on Sustainable Land Management to Enhance Food Production of APEC Members on 28 – 30 November, 2012, in Chiang Mai, Thailand under the sponsorship of the Asia-Pacific Economic Cooperation (APEC). We wish to thank APEC for permission to publish this manuscript.

References

Allran, J. W. and Karasov, W. H. 2000, Effects of Atrazine and Nitrate on Northern Leopard Frog (RANA PIPIENS) Larvae Exposed in the Laboratory from Posthatch Through Metamorphosis. Env. Tox. & Chem. Vol. 19, No. 11, pp. 2850 – 2855.

Alston, J. M., Beddow J. M., and Pardey P. G. 2009, Agricultural research, productivity, and food prices in the long run. Science, Vol. 325 (5945), pp. 1209 – 1210.

Andrews S. S., Karlen D. L., and Cambardella C. A. 2004, The soil management assessment framework: A quantitative soil quality evaluation method. Soil Science Society of America Journal, Vol. 68, pp. 1945 – 1962.

Aude E., Tybirk Bruus K., and Pedersen M., 2003, Vegetation diversity of conventional and organic hedgerows in Denmark, Agric Ecosyst and Environ, Vol. 99, pp. 135 – 147.

Bengston D. N., Xu G., and Fan D. P. 1998, Attitudes toward ecosystem management in the U. S.. Society Nat. Resources, Vol. 14, pp. 471 – 487.

Brunson M. W. and Steel B. S. 1996, Sources of variation in attitudes and beliefs about federal rangeland management. Journal of Range Management, Vol. 49, pp. 69 – 75.

Doran J. W., and Parkin T. B. 1994, Defining and assessing soil quality. pp. 3 – 21. In: J. W. Doran et al. (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. No. 35. SSSA, Madison, WI.

Downing A. S., van Nes E. H., Mooij W. M., and Scheffer M. 2012, The resilience and resistance of an ecosystem to a collapse of diversity. PLoS ONE, Vol. 7, No. 9, pp. 46135. Doi: 10. 1371/journal. pone. 0046135.

EPA. 2011, Draft: Global anthropogenic non-CO_2 greenhouse gas emissions: 1990 – 2030. Office of Atmospheric Programs, Climate Change Division, U. S. Environmental Protection Agency, Washington, DC.

Eswaran H., Almaraz R., van den Berg E., and Reich P. 1997, An assessment of the soil resources of Africa in relation to productivity. Geoderma, Vol. 77, pp. 1 – 18.

FAO. 2012, Conservation agriculture. Website at www. fao. org/ag/ca/index. html (Confirmed on Nov. 11, 2012).

FAO. 2009, The state of food insecurity in the world: Economic crises-impacts and lessons learned. United Nations, Rome, Italy.

FAO (Food and Agriculture Organization of the UN). 2002, FAO- STAT Statistics Database. Rome, Italy: UN Food and Agriculture Organization.

Fuhrer J. 2003, Agroecosystem responses to combinations of elevated CO_2, ozone and global climate change. Agriculture Ecosystem and Environment, Vol. 97, pp. 1 – 20.

Giller K. E., Witter E., Corbeels M. and Tittonel, P. 2009, Conservation agriculture and smallholder farming in Africa: The heretics' view. Field Crops Res. Vol. 114, pp. 23 – 34.

Gilles J., and Valdivia C. 2009, Local Forecast Communication in the Altiplano. Bulletin of the American Meteorological Society BAMS (1 January), pp. 85 – 91.

Glenn J. C., Gordon T. J., Florescu E., and Starke L. 2008, The State of the Future. 2008 Millennium Project. World Federation of the United Nations Associations.

Gold M. A., Rietveld W. J., Garrett H. E., and Fisher R. F. 2000, Agroforestry nomenclature, concepts, and practices for the USA.

pp. 63 – 77. In: H. E. Garrett, W. J. Rietveld and R. F. Fisher (eds.) North American Agroforestry: An Integrated Science and Practice. American Society of Agronomy, Madison, WI.

Griffiths, B. S., Ritz K., Bardgett, R. D., Cook R. Christensen, S., Ekelund F. Sorensen S. J., Baath E., Bloem J., de Ruiter P. C., Dolfing J., and Nicolardot B. 2000, Ecosystem response of pasture soil communities to fumigation-induced microbial diversity reductions: An examination of the biodiversity-ecosystem function relationship. Oikos Vol. 90, pp. 279 – 294.

Gugino B. K., Idowu O. J., Schindelbeck R. R., van Es H. M., Wolfe D. W., Moebius-Cline B. N., Thies J. N., and Abawi G. S. 2009, Cornell soil health manual, Edition 2.0, Cornell University, Geneva, NY.

Henao J., and Baanante C. 2006, Agricultural production and soil nutrient mining in Africa: Implications for resource conservation and policy development, An International Center for Soil Fertility and Agricultural Development (IFDC), Muscle Shoals, Alabama.

Hobbs P. R., Sayre K. and Gupta R. 2008, The role of conservation agriculture in sustainable agriculture. Phil. Trans. R. Soc. Vol. 363, pp. 543 – 555.

Knowler D. and Bradshaw B. 2007, Farmers' adoption of conservation agriculture: A review and synthesis of recent research. Food Policy Vol. 32, pp. 25 – 48.

Lal, R., Mokma D., and Lowery B. 1998, Relation between soil quality and erosion. pp. 237 – 257. In: R. Lal (ed.) Soil Quality and Soil Erosion, CRC Press, Boca Raton, FL.

Lassoie J. P., and Buck L. E. 2000, Development of agroforestry as an integrated land use management strategy. pp. 1 – 29. In: H. E. Garrett, W. J. Rietveld and R. F. Fisher (eds.) North American Agroforestry: An Integrated Science and Practice. American Society of Agronomy, Madison, WI.

Lin B. B. 2011, Resilience in agriculture through crop diversification: Adaptive management for environmental change. BioScience, Vol. 61, pp. 183 – 193.

Matson P. A., Parton W. J., Power, A. G. and Swift, M. J. 1997, Agricultural intensification and ecosystem properties. Science, Vol. 277, pp. 504 – 509.

McLoud P. R., Gronwald R., and Kuykendall, H. 2007, Precision agriculture: NRCS support for emerging technologies. Agronomy Technical Note No. 1, Natural Resources Conservation Service, U. S. Dept. of Agriculture, Washington, DC.

Mercado A. R. 2009, Tree-vegetable interaction in vegetable agroforestry systems. Progress report available on the web at http://www.google.com/url? sa = t&rct = j&q = &esrc = s&source = web&cd = 1&ved = 0CDcQFjAA&url = http% 3A% 2F% 2Fsanrem.cals.vt.edu% 2F1123% 2FJun% 2520Mercado% 2520VAF% 2520complementary% 2520systems.ppt&ei = AAmsUIHHJsSF2gXvvYG4Bw&usg = AFQjCNHCw_XdP45s1nReRapPTvLtA3rCgA&sig2 = yRXuww8FMOsNBIdeXsY3wA.

Mercado A. R., Duque-Pinon C., Reyes M., Palada M., Faustino F. and Engle L. 2009, Vegetable-agroforestry (VAF) systems: Understanding vegetable-tree interaction is a key to successful vegetable farming enterprise. The 2nd World Congr. Agroforest. (24 – 28 August, 2009), Nairobi, Kenya.

Millennium Ecosystem Assessment. 2005, Ecosystems and human well-being: current state and trends. Island Press, Washington, D. C.

Motavalli P. P., Kremer R. J., Fang M., and Means N. E. 2004, Impact of genetically-modified crops and their management on soil microbially-mediated plant nutrient transformations. Journal of Environtal Quality, Vol. 33, pp. 816 – 824.

Motavalli P. P., Nelson K. A., and Bardhan S. 2012, Development of a variable source nitrogen fertilizer management strategy using enhanced efficiency nitrogen fertilizers. Soil Science. Vol. 177, pp. 708 – 718.

Mungai N. W., Motavalli P. P., Nelson K. A., Kremer R. J. 2005, Differences in yields, residue composition and N mineralization dynamics of Bt and non-Bt maize. Nutrient Cycling in Agroecosystems, Vol. 73, pp. 101 – 109.

NRCS. 2011, Soil quality for environmental health. Natural Resources Conservation Service, U. S. Dept. of Agriculture website: http://soilquality.org/home.html#. (Confirmed Nov. 20, 2012).

Parry M. L., Rosenzweig C., Iglesias A., Livermore M., and Fischer G. 2004, Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change, Vol. 14, pp. 53 – 67.

Quiroz R., Valdivia R., Pun H. H., Velarde C. U., Reinoso J., and Mares V. 2006, Pursuing the Millennium Development Goals in the Andean Altiplano-Building on CIP project experience with poverty alleviation and sustainable development. Mountain Res. Devel. Vol. 26 (1), pp. 15 – 19.

Reyes M. R. 2008, Progress report: Agroforestry and sustainable vegetable production in Southeast Asian Watersheds. An ASABE Meeting Presentation, Paper Number 08515, St. Joseph, MI.

Roberts P. C., Rust R. H., and Larson W. E. 1994, Preface. Proceedings of site specific management for agriculture system, Minneapolis, MN, ASA-CSSA-SSSA, Madison, WI. pp. 13 – 14.

Robertson G. P., and Swinton S. M. 2005, Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. Frontiers in Ecology and Environment, Vol. 3, No. 1, pp. 38 – 46.

Rydén p. 2010, Linking sustainable land management science to policy advice and decision-making. Powerpoint presentation available on the web at http://www. agri4d. se/document/56_124_13% 20Ryden% 20Making% 20land% 20productivity% 20research% 20policy% 20relevant. pdf(confirmed on Nov. 11, 2012).

Scherr S. J. 1999, Soil degradation: A threat to developing-country food security by 2020. International Food Policy Research Institute. Food, Agriculture, and the Environment Discussion Paper 27, Washington, DC.

Selman M. , Greenhalgh D. R. , and Sugg, Z. 2008, Eutrophication and hypoxia in coastal areas: A global assessment of the state of knowledge. World Resources Institute, Washington, DC.

Smith P. , Martino D. , Cai, Z. , Gwary D. , Janzen H. , Kumar P. , McCarl B. , Ogle S. , O'Mara F. , Rice C. , Scholes B. , and Sirotenko O. 2007, Agriculture. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer(eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Smyth A. J. , and Dumanski J. , 1993, FESLM: An international framework for evaluating sustainable land management. World Soil Resources Report. Food and Agriculture Organization of the United Nations, Rome, Italy.

Steel B. S. , Shindler B. and Brunson M. W. 1998, Social acceptability of ecosystem management in the Pacific Northwest. In Ecosystems management: A social science perspective, Soden, D. , Lamb, B. L. and Tennert, J. R. (eds.) pp. 147 – 160. Kendall-Hunt, Dubuque, IA.

Tilman D. , Fargione J. , Wolff B. , D'Antonio C. , Dobson A. , Howarth R. 2001, Forecasting agriculturally driven global environmental change. Science, Vol. 292, pp. 281 – 284.

Tilman D. , Cassman K. G. , Matson P. A. , Naylor R. , and Polasky S. 2002, Agricultural sustainability and intensive production practices. Nature, Vol. 418, pp. 671 – 677.

Torsvik V. , Goksoyr J. , and Daae F. L. 1990, High diversity in DNA of soil bacteria. Applied and Environmental Microbiology Vol. 56, pp. 782 – 787.

UNEP. 1999, Global Environment Outlook – 2000. United Nations Environment Programme. Earthscan Publications, London. http://www. unep. org/geo2000

van der Heijden M. G. A. , Klironomos J. N. , Ursic M. , Moutoglis P. , Streitwolf-Engel R. , Boller T. , Wiemken A. , Sanders I. R. 1998, Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity. Nature, Vol. 396, pp. 69 – 72.

Wardle, D. A. , and K. E. Giller. 1997, The quest for a contemporary ecological dimension to soil biology Soil Biol. Biochem. Vol. 281, pp. 549 – 1554.

World Bank. 2006, Sustainable land management: Challenges, opportunities, and trade-offs. The International Bank for Reconstruction and Development/The World Bank, Washington, DC.