SOLAW TR11

Critical choices for crop and livestock production systems that enhance productivity and build ecosystem resilience

SOLAW Background Thematic Report – TR11

C. Neely and A. Fynn

Acknowledgements

The authors would like to thank Caterina Batello, Sally Bunning, Theodor Friedrich, Rich Conant, and Stefan Schlingloff for their useful insights and comments during the development of the extended executive summary and the full report.

Table of contents

List of figures

Abbreviations and acronyms

AF	Agroforestry
CA	Conservation agriculture
BAU	Business as usual
CH_4	Methane
CO_2	Carbon dioxide
CF	Conservation farming
COMESA	The Common Market for Eastern and Southern Africa
CSO	Civil society organization
CT	Conservation tillage
FAO	Food and Agriculture Organization of the United Nations
FFS	Farmer Field School
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIAHS	Globally Important Agricultural Heritage Sites
HM	Holistic management
ICLS	Integrated crop-livestock systems
INM	Integrated Nutrient Management
IPNM	Integrated Plant Nutrient Management
IPM	Integrated Pest Management
LCA	Life Cycle Analysis
MDG	Millennium Development Goals
N	Nitrogen
N_2O	Nitrous oxide
NGO	Non governmental organization
PES	Payment for Ecosystem Services
REDD	Reducing Emissions from Deforestation and Degradation
SARD	Sustainable Agriculture and Rural Development
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SLM	Sustainable Land Management
SPI	Sustainable Production Intensification
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environmental Programme
WOCAT	World Overview of Conservation Approaches and Technologies

Executive summary

Trends

The natural resource base on which agriculture depends has declined faster in the past 50 years than at any other time in human history, owing to increased global demand and degradation of land, water and biodiversity. In the same period, 75 percent of the crop genetic base has been lost. By conservative estimates, a quarter of the world's population now depends directly on land that is being degraded. While there are more hungry people in Asia than other regions, sub-Saharan Africa suffers from long-term food insecurity, with two-thirds of the productive land area in the region affected by land degradation. If current trends go unchanged, by 2025 the African continent will only be able to feed one-quarter of its population.

Degradation is caused by unsustainable agricultural production methods, especially intensive tillage (which promotes erosion of some 25 000 million tonnes of topsoil per year), nutrient mining, poor soil cover, and pollution from conventional intensive farming, deforestation and poor grazing management. Mechanical soil tillage and removal of vegetation destroy soil structure and accelerate soil erosion by exposing the soil to the impacts of rain and wind. Salinization of unsustainably irrigated land is also a major factor for soil degradation.

Six million children die of starvation every year, or 17 000 a day. A further 8 000 children die each day of preventable malnutrition and malnutrition-related diseases. Some 1.1 billion people do not have access to clean water. Agriculture accounts for 70 percent of water use, and some 24 percent of irrigated land is affected by salinity (FAO, 2007b). According to current trajectories, water use through evapotranspiration during crop production will almost double by 2050, yet water is essential for both drinking (2-5 litres per person per day) and for production.

Different food products make different demands on water: 1 litre of wheat requires 1 500 litres of water, and 1 kg of meat requires 15 000 litres. It takes approximately 3 000 litres to meet one person's daily food needs; 1 000 times more water is needed to feed the human population as to satisfy its thirst. There is enough water for the world's food needs to be met over the next 50 years, but allocation, provision, and efficiencies must be radically improved to avoid further water conflicts, which are already occurring.

Agricultural water loss can be reduced by different crop choices and crop and livestock management practices; eliminating delivery inefficiencies and unproductive water losses; improving system design; and keeping soils covered with crop residues, other organic materials, permanent crops, cover crops and 'green manures'. More efficient water management is implicit in sustainable land management (SLM) systems, and can be achieved in the context of the kind of sustainable production intensification (SPI) needed to meet upcoming food demands on the same global agricultural area footprint.

Agriculture contributes directly as much as 14 percent of anthropogenic greenhouse gases (GHG) globally; this figure more than doubles when related land-use change is included. Livestock has come under scrutiny for the associated environmental consequences regarding water use and GHG emissions (particularly CH_4 and N_2O). Recent growth in the sector has lead to the industrialization of livestock production which is, in many cases, shifting from smallholder farms to large-scale commercial operations, often near urban centres. Meat production is projected to more than double over the next 50 years, a trend associated with improvements in living standards and expectations, especially in Asia.

While climate change exacerbates issues associated with the dwindling land and water resource base, it may prove to be a catalyst for accelerating uptake of sustainable agricultural practices that lead to enhanced ecosystem processes and long-term resilience.

This report provides an overview of systems of production that reduce negative agricultural impacts on use of soil, water and biological resources; many highlighted approaches regenerate ecosystem resilience and ecosystem services. This report also identifies critical practical issues for effective transition to such systems.

Because of the evolution of different practices and production systems, an overlap of the approaches featured is unavoidable, particularly concerning the elements within them (e.g. maximizing crop residue, enhancing nutrient and water cycles, etc.). As a specific example, the use of leguminous 'fertilizer trees' are integrated into conservation agriculture, agroforestry and permaculture. Users and developers of different production systems are continually seeking greater efficiencies and increased yield-to-cost/input ratios. Emerging innovations tend to borrow and synthesise the best elements from elsewhere. While it is beyond the scope of this report to provide a detailed cross-reference of SLM production systems a comprehensive analysis would prove valuable.

Ecosystem processes and ecosystem services

Increasingly, the environmental and/or economic values of ecosystems are being recognized and referred to as ecosystem services. Among the many ecosystem services associated with transitions to SLM systems are the regulating of soil and air temperatures, prevention of soil degradation, reduced dust load in the atmosphere, increased water quantity and quality through infiltration, capture, recharge and buffering, decreased risk of flooding and drought, conserving and enhancing biological diversity and improved habitat for beneficial organisms (e.g. enhanced pollination, pest and disease control, soil biota and wildlife).

Over the last decade there has been a strong trend towards taking an ecosystem approach to land management. This strategy for integrated and sustainable management of land, water and living resources recognizes human beings as an integral part of ecosystems. Also, increasing attention is being paid to eco-agriculture, which facilitates the convergence of agriculture, biodiversity and the stabilisation of rural livelihoods by recognizing producers and communities as stewards of biodiverse agriculture. A third trend that has garnered greater interest is management at the landscape scale, which takes into account the actors and stakeholders (human and otherwise) within a landscape; considers their rights, needs, desires and goals; and develops balanced and integrated solutions that lead to enhanced ecosystem function. Climate change is likely to add further momentum to these trends as countries gear up for greener economies and seek to shorten food chains while promoting food and nutrition security. At the same time, the need to adapt to climate variability provides incentives for the adoption of land management strategies that will lead to enhanced provision of ecosystem services as an adaptation strategy.

Agro-ecology

Agro-ecological principles promote a whole-system approach to agriculture and food systems, using methods sourced from traditional knowledge, alternative agriculture, advanced science and technologies and local food systems. Agro-ecology employs, *inter alia*, minimum and no-till methods, rotational grazing, intercropping, crop rotation, crop-livestock integration, intra-species variety and seed saving, and pest management rather than 'control'. Agro-ecology also encourages beneficial insects and the enhancement of beneficial biota including mycorrhizae and nitrogen-fixers; and conserves resources, including energy, water (through dry farming and efficient irrigation), soil nutrients and SOM stocks.

Sustainable land management

Soil management and the effectiveness of the water and nutrient cycles are closely related, owing in part to the key water-retentive quality of soil carbon, which makes up 50 percent of soil organic matter or SOM, and its inverse correlation with soil density, except in specialized systems such as hydroponics and high input arid land systems where nutrients are provided in irrigation water. Soil fertility, productivity and resilience depend upon organic matter management. Production systems that ensure efficient use of soil and water resources and enhance biological diversity positively affect the provision of natural resources and allow self-regeneration of ecosystems by maintaining ecological functions (both regulating and life support functions). These systems, practices and approaches come under the umbrella of Sustainable Land Management (SLM), and represent qualitative changes in management of natural resources inputs. They bring reductions in energy expenditure and GHG emissions and provide a range of socio-cultural benefits.

The specific approaches discussed in this report represent a number of identified best practices to enhance productivity and build the resilience of ecosystems. However each has its potential drawbacks depending on the context and potential constraints to widespread adoption.

Sustainable land management encompasses, among others, elements and principles of agricultural land management concepts such as conservation agriculture, agro-ecology, eco-agriculture, integrated pest and plant nutrient management, which complement each other in their sustainability aspects. Further complements are achievable, to different degrees, employing components of permaculture, agroforestry, traditional agriculture, organic agriculture and well as certain livestock-based systems; including pastoral and integrated crop-livestock systems. These are all based, to a lesser or greater extent, on agro-ecological principles. Different scenarios suggest the selection of a menu, or wise combination, of SLM options adapted to local human and environmental contexts. Key features of SLM systems include (FAO, 2007b):

- greater resource efficiency (soil, water, biological, and energy), through waste reduction and on-site recycling of nutrients;

- enhanced biological interactions to promote ecological processes and services;

- maintained soil cover and enhanced soil organic matter, which enhance soil life positively affecting soil tilth, water infiltration and water retention; and

- reduced or eliminated use of non-biotic interventions such as mechanical soil tillage and synthetic inputs, which often come with high environmental costs and are subject to availability and fluctuations in commodity prices.

Sustainable production intensification

The striking need to feed an extra 2.5 billion people (plus the 1 billion who are already hungry) within the next 40 years on the same productive footprint, while decreasing the environmental impacts of the sector, is leading the drive for Sustainable Production Intensification (SPI) of agricultural systems. Many SLM systems open pathways towards SPI and share important principles:

- synergistic solutions that resolve divergent problems with multifaceted solutions;

- taking advantage of local knowledge and ecosystem peculiarities; and

- increased and more stable yields compared to conventional systems.

"Sustainable production intensification responds to the need to increase opportunities for crop production to address the current and future environmental threats the world is facing and ultimately respond to the need to increase food production for the forecasted increase in human population. An important aspect of SPI is to manage biological processes sustainably to optimize production." (FAO, 2010a)

Different SLM systems

The following production systems can be used to enhance ecosystem processes while increasing productivity; but all practices and approaches must be implemented according to sustainability principles.

Conservation agriculture – (CA) systems seek to conserve natural resources while increasing yields and resilience. CA is grouped around three core principles that, applied simultaneously, provide a basis for sustainability owing to synergetic effects: minimal soil disturbance, permanent soil cover and crop diversity. Established CA systems provide improved rainwater infiltration, and lead to: reduced runoff, evaporation and erosion; increased biodiversity and soil organic matter; improved soil structure; higher yields and reductions in labour, synthetic fertilizer, pesticide and use of fossil fuels. Because of its proven track record, CA is being promoted by FAO in developing and emerging economies — as are many other SLM systems and approaches.

There are around 116 million ha under conservation agriculture worldwide. Conservation agriculture with trees incorporates their use to enrich soils and provide fodder for animals; in particular *Faidherbia albida* is used to take advantage of its nitrogen-rich leaf fall during the growing season, a feature of its unique reverse phenology. CA lends itself to being complemented with other SLM concepts, such as integration of crops and livestock as well as trees (agroforestry), integrated pest management (IPM), integrated plant nutrient management (IPNM).

Organic agriculture systems – avoid synthetic fertilizers, pesticides and genetically modified organisms; and can lead to reduced air, soil and water pollution, compared to baseline practices. As for other approaches, the choice of system, its component practices and the way they are applied can significantly affect net agro-ecological environmental benefits. Key wealth creation opportunities exist for producers in the developing world producing crops for sale in developed countries, where demand for organic products has burgeoned. Medium- and large-scale organic production often includes mechanical tillage and requires inputs/imports of organic material such as compost, mulch to maintain soil productivity. Over 32 million ha worldwide are now farmed organically by 1.2 million farmers, with organic wild products harvested on around 30 million ha.

Traditional agricultural systems – comprise indigenous forms of ecological agriculture resulting from the co-evolution of social and environmental systems. Specific use of environmental knowledge and natural resources results in a complex interface between productive and natural systems. Careful management of these systems can result in higher yields. Traditional agriculture is characterized by a high degree of complexity and plant biodiversity. Incorporating polycultures and/or agroforestry systems, these heterogeneous systems cover 5 million ha worldwide, some of which are exemplified in the Globally Important Agricultural Heritage Sites (GIAHS). Forms of traditional agriculture need to be assessed against current and regionally appropriate criteria because some forms, such as slash-and-burn, are not sustainable in modern contexts, with current population pressures.

While systems associated with SLM share common features (below), these are not universal criteria:

- conservation of soil and water resources compared to conventional practices;
- reduced use of artificial inputs (including chemicals such as insecticides, pesticides, herbicides, artificial fertilizers);
- reuse of on-site nutrients;
- interweaving of different elements on the same footprint to increase yield and crop diversity on the same area;
- more permanent systems compared to business as usual, e.g. avoiding tillage;
- increasing biodiversity, stability and complexity of productive systems over time;
- provision of increased ecosystem services from the productive system to surrounding communities; and
- decreased financial net costs to the producer and human communities over the long term.

A complete mapping of SLM features and criteria would prove a useful parallel adjunct to the mapping of different SLM systems.

Agroforestry systems – represent the integration of woody perennials with crops and/or livestock to access the beneficial interactions between these, and balance ecological needs with the sustainable harvesting of tree and forest resources. Knowledge of the positive interactions within systems and of contraindicated combinations is essential, as for all integrated modalities. There are five main forms of agroforestry: **alley cropping, forest farming, silvopastoralism, riparian forest buffers and windbreaks.**

Alley cropping – is the introduction of trees to productive land and the planting of crops between them. **Forest farming** introduces high-value non-timber species under forest canopies, providing diversified income while high-quality trees are being grown for wood products. **Silvopastoralism systems** include the introduction of trees into grazing areas, providing shade and shelter, increased resilience and, in some cases, improved forage quality. Silvopastoralism can bring dramatic results: 20 years ago, in the Shinyanga region of Tanzania, soil erosion was such that dust storms were common; today the activity of the Shinyanga Land Rehabilitation Programme (HASHI) means that woodlots yield firewood and building timber, while fruit orchards provide food, and fodder trees supply protein-rich feed for livestock. Agroforestry systems, combined with sustainable crop production such as conservation agriculture, would add or further strengthen ecosystem services of those crop production concepts for enhanced sustainability.

Grasslands represent some 70 percent of global agriculture land area; unfortunately as much as 35 percent of the grasslands are degraded. The livestock sector provides livelihoods to 1.3 billion people, mostly smallholder farmers and pastoralists in the developing world. Rapidly increasing demand for livestock products means that the production footprint of livestock must significantly decrease. There are both intensive and extensive systems that can contribute to production and environmental goals.

Integrated crop-livestock systems (ICLS) – encompass diversified components and capitalize on the effective interaction between crops and crop-related products to provide feed for livestock and the forage and livestock component for enhanced system diversity, including manure to fertilize crops for on-site or in-landscape nutrient cycling. Although they have been a feature of traditional agriculture for centuries, ICLS are now benefiting from synergistic components provided by the modern crop, livestock and agroforestry sectors. ICLS can positively affect biodiversity, soil health, ecosystem services, forest preservation and adaptation to and mitigation of climate change. Finally, they can prove highly profitable and advantageous, under modern economic conditions, as compared with intensive large scale specialized operations. Variants include systems with or without trees or aquaculture, and agropastoral systems with or without trees.

Cropping according to **conservation agriculture** methods allows cropping to be integrated with other land uses, notably grass leys as part of the rotation for grazing and tree crops. Recently, efforts have been made to develop systems in which the shift from crops to pasture can be managed without soil tillage. Pasture cropping combines cropping and grazing into one land management system that benefits both uses. Winter and summer crops can be grown without destroying the perennial pasture base. Crops are sown into existing pasture; this stimulates the perennial seedlings in a highly beneficial way, provides up to six months of extra grazing, radically reduces cropping costs and provides protective soil cover. This system has achieved a doubling of soil carbon levels from 2 to 4 percent over ten years. This has been made possible by employing conservation agriculture principles, showing the potential of integrated crop livestock systems for SLM.

Planned grazing strategies recognize that it is not livestock per se but the choice of grazing management system and its suitability for the landscape, that leads to positive or negative effects. In recent decades grassland management systems have been developed that not only reduce impacts but also use livestock as a tool to enhance productivity and ecosystem function. The best known is Holistic Management (HM), which uses timed controlled mob grazing in an attempt to replicate the behaviour and effects of wild herds of ungulates in original ecosystems; particularly in semi-arid areas. After the co-evolution of grass species and wild ungulates with predators in Africa for example, modern settlements and agricultural patterns have mostly led to interrupted symbiotic cycles; resulting in greater erosion and landscape degradation. HM has been used effectively on different continents to restore grassland ecosystems in the absence of increased rainfall or irrigation. Other systems also exist whereby livestock are used as a land management tool; these are found within the repertoires of traditional agriculture and permaculture.

Improved pastures can be achieved for example by introducing leguminous plants or trees (enrichment planting) into grazing lands. This increases soil nitrogen, provides ground cover and keeps soils cooler, moister, less eroded and less compacted; allowing stressed systems to recover. Trees can be planted for fodder, or the leguminous 'fertilizer trees' can meet this need. Degraded land can recover within exclosures, which can be planted with leguminous species, excluding livestock until these have matured enough to withstand grazing.

Fire prevention can play an important part in different systems because fire mineralizes essential organic matter to atmospheric CO_2 This requires special care in drylands, when dry surface residues are present, an important factor for saving water in these regions. Firebreaks can prevent the spread of accidental fires in forests or grasslands, yet fire is an integral component of many grassland systems, and fire suppression can contribute to woody encroachment. In pastures, controlled burning is a strategy to reduce fire intensity, fire frequency and the resulting damage. In cropping systems reduced burning of crop residues is a necessity for restoring soil organic matter and soil carbon and for supplementary animal feed.

When considering one approach over another, and in selecting the appropriate menu of SLM options, there will be trade-offs associated with each selection. The final choice will be determined by assessment of greatest net benefit in ecological, production and sociocultural dimensions, which will be determined by the difference between the effects of new management practices and a baseline of either pre-project practices or extrapolated activity under business as usual.

Incentives for sustainable land management

Policy instruments designed to embrace the true costs of externalities associated with degrading ecosystem services are key to ensuring that those who manage ecosystem processes are provided with incentives to carry out sustainable practices. There are numerous regulatory (stick) and reward (carrot) instruments designed with the intention of promoting sustainable management of ecosystems. These include those that offer agro-environmental payments for ecosystem services (PES) and those that offer disincentives such as taxes for unsustainable practices. Diverse instruments are being actively developed and implemented by international and national NGOs, business, industry, and governments. Policies must be put in place to promote the scaling-up of sustainable land management. Investments will be required in associated capacity development related to technical aspects as well as how farmers and pastoralists can access financial incentives for good practice.

Summary

While the interconnectedness of globalized systems brings extreme challenges to producers and the environment, particularly in the context of developing countries, this interrelation also provides opportunities. Agriculture is at the nexus of convergent world crises, and a transition to sustainable agriculture will prove catalytic, beyond the agricultural sector. At the centre of the crises and opportunities facing agriculture is the accumulation of organic carbon as soil organic matter and biomass.

Management systems needed to optimize the sustainability of agriculture worldwide are available today and have proven yields. The synthesis and appropriate deployment of large-scale regional sustainable agriculture development plans, alongside applied research, would be a logical next step. These would begin with upscaling the SLM best practices on a regional basis. Scaling issues include the potentially complex applicability of different systems, the need for a participatory process, and the need for mechanisms and networks in support of producers to be in place while biodiverse agro-ecosystems are becoming established.

There are many issues and challenges facing the supply and use of soil, water, and biological resources in agriculture. The majority of these constraints can be alleviated by a sustainable and efficient use of this natural capital, and by supporting the ecosystem processes that regenerate it. Natural resources are finite and true costs cannot be externalized indefinitely.

1. Introduction and background

1.1 Purpose and structure of this report

This report provides an overview of systems of production that reduce negative impacts on the use of soil, water and biological resources in agriculture. This report demonstrates that an ecological approach will regenerate ecosystem resilience and services. This review is not meant to be exhaustive, but presents key approaches and discusses the importance of choosing elements of sustainable crop and livestock systems that bolster ecological processes, while also identifying practical aspects for effective transitions to such systems.

This report describes and provides: a brief overview of trends in land and water management for agriculture; the rationale for optimizing resource efficiency and managing ecosystem processes; recent trends and principles; systems for sustainable land management; challenges to transitioning to and scaling up sustainable land management; and, conclusions and recommendations.

1.2 Global trends in soil and water management

Agriculture

Recent decades have seen the development of certain global trends in agriculture, which tend to pull other trends in their wake. The first trend is accelerated natural resource (land, water and biological diversity) degradation, driven by burgeoning human populations and unsustainable agricultural and other land-use practices. Second, in line with population growth and increasing per capita food demands, and driven by technological innovation and the desire to increase profits, recent decades have seen the intensification of cropping and livestock systems. This has been accompanied by a specialization and concentration of the different production sectors, with environmental costs externalized spatially and in time. This trend has been accompanied by an unprecedented one billion people hungry, food price fluctuations and the redistribution of land assets from the local producer to the global agribusiness. A third, and more positive trend, has been the resurgent interest in agriculture on the global agenda, matched with environmental concerns. This has led to a greater implementation of SLM approaches that improve the efficiency of soil and water resource use and bolster future provision of these resource — whilst building a foundation for long-term production for farmers.

This last trend has been influenced by an understanding that sustainable management of land, water and biological diversity underpins production and socio-economic benefits, as well as by increased consumer demand for safe and sustainably produced products.

Finally, a mega-trend has been in evidence in recent years encompassing climate change, global trade and land degradation, and which began before the Industrial Revolution. It is the convergence of multiple crises pulled together by the explosion in human connectivity and adaptive success that is known as globalization. What were once isolated events have ever more unplanned effects in diverse regions and sectors of human activity, so that, in effect, *there are no more isolated events*. Agriculture, which by its success has fuelled industrialization, and continues to do so, finds itself at the nexus of these crises. Besides the obvious challenges, that positioning brings opportunities.

Land resource degradation

The natural resource base on which agriculture depends has declined faster in the past 50 years than at any other time in human history, owing to increased global demand and degradation of land, water and biodiversity. In the same period, 75 percent of the crop genetic base has been lost. By conservative estimates, a quarter of the world's population now depends directly on land that is degraded. While there are more hungry people in Asia than other regions, sub-Saharan Africa suffers from long-term food insecurity, with two-thirds of the productive land area affected by land degradation.

If current trends go unchanged, by 2025 the African continent will only be able to feed one-quarter of its population. For these reasons, and because of additional challenges on the continent such as disease and conflict, Africa, notwithstanding specific successful examples, has provided the greatest and most complex challenge to successful implementation of SLM. It is critical to advance SLM best practices technologically, but also to continue to address socio-economic and political constraints to widespread adoption.

Beyond inappropriate land-use changes that have resulted in loss of productive resources, it is currently estimated that more than 20 percent of productive land is severely degraded. Grasslands, including rangelands, shrub land, pastureland and cropland sown with pasture trees and fodder crops represent almost 30 percent of the world's agriculture area (FAO, 2006a), however, grassland degradation is estimated to range from 20–35 percent; and some 38 percent of croplands are degraded (UNCCD, 2009).

In agricultural systems, degradation is caused by unsustainable production methods, especially mechanical soil tillage, which promotes erosion of some 25 000 million tonnes of topsoil per year, nutrient mining, poor soil cover and pollution from conventional intensive farming, deforestation and poor grazing management. Tilling soils temporarily boosts yields but over time leads to compaction, loss of SOM (including flushes of CO_2) and soil nutrients, and reduced soil water holding capacity, thus removing the fragile basis for soil system equilibrium. Mechanical soil tillage and removal of vegetation further destroy soil structure and accelerate soil erosion by exposing the soil to the impacts of rain and wind, and can lead to crusting, further decreasing infiltration and exacerbating runoff and severe erosion. Excessive tillage also leads to build-up of soil toxicity, and reduces or eliminates populations of essential soil organisms (FAO, 2007b).

In grassland systems, the dominant degradation forces are associated with burning and the management of livestock that leads to overgrazing. Overgrazing occurs when plants are not allowed to regenerate before they are grazed again. More specifically, this occurs when plants are exposed to animals for too many consecutive days or if animals leave the area but return to the grazing area before plant recovery; and/or if animals are allowed to graze immediately following plant dormancy. Overgrazing generally leads to reduced diversity of plant species, loss of plant and root systems and ultimately bare ground. Fire also causes bare ground, greatly diminishing soil microbial activity and organic matter content in the upper soil horizons.

Agrobiodiversity, including the diversity of crops, trees, grasslands and livestock as well as resource biota such as pollinators, decomposers and nitrogen fixers, plays a critical role in ecosystem resilience. The closer a farming system is to a monoculture, the more susceptible it becomes to pests and diseases, increasing the risks to livelihoods and food security. As an example, transitioning biodiverse farms to monocrop biofuel crops is likely to play to this disadvantage; higher amounts of more powerful pesticides are then needed in a battle that cannot be won. Pesticides affect and kill non-target organisms, including natural pest predators, leading to further pest build-ups and new and more virulent outbreaks. Such systems can, in turn, result in severe contamination of water resources and affect the biodiversity of entire landscapes by destroying the lower end of the food web.

Agricultural water use

Feeding more people with diets that make greater use of natural resources will require more and more water if conventional agricultural models are followed. Agriculture currently accounts for 70 percent of water use. A major transition to more resource-efficient sustainable land management practices is needed if already limited global water supplies are to support a 70 percent increase in food production by 2050.

According to current trajectories, water use through evapotranspiration during crop production will almost double by 2050 (IWMI, 2007), yet water is essential for both drinking (2-5 litres per person per day) and production. This does not even account for the expected temperature increase under a climate change scenario, which will further increase the unproductive evaporation of water from bare soil surfaces. Different food products make different demands on water; for example, 1 kg of wheat requires 1 500 litres of water, and 1 kg of meat requires 15 000 litres. It is estimated that, on average, it takes 3 000 litres of water to meet one person's daily food needs. A thousand times more water is needed to feed the human population than to satisfy its thirst.

Some 24 percent of irrigated land is affected by salinity (FAO, 2007b). Intensive irrigation exacerbates fertilizer leaching into groundwater and water bodies, causing eutrophication that kills aquatic life, changes food chain species composition, and degrades the complexity that brings resilience. Highly irrigated land tends to develop salinity in arid/semi-arid zones and waterlogging in humid areas. Dams can have a massive disruptive effect on river basin and catchment hydrology. Excessive pumping of groundwater, exceeding the replenishment rates of the aquifer, lowers water tables and compromises human and other communities.

There is enough water for the world's food needs over the next 50 years, but allocation, provision and efficiencies must be radically improved to avoid water conflicts, which are already occurring. Agricultural water loss can be reduced by wiser crop and land-use choices, eliminating delivery inefficiencies, improving agro-ecosystem design, reducing unproductive evaporation by maintaining crop residues, and keeping soils covered with permanent crops, cover crops including green manures, mulch, compost and other organic matter.

Water deficits are responsible for an alarming trend in grain imports in medium-sized countries and food insecurity. Even some countries that are rich in arable land are beginning to import grain. Since global food supply is export or import-dependent, when medium- and large-sized exporting countries encounter enduring freshwater supply issues, all related crises are exacerbated. As of 2009, drought conditions were evident in the countries that provide two-thirds of the global agricultural output (deCarbonnel, 2009). Diversified small-scale agriculture will be critical in mitigating the effects of such phenomena into the future, not just in developing countries. A lack of credit for farmers in 2008-2009 compromised their ability to buy fertilizers and will limit subsequent global production. The effects of droughts will be exacerbated by the reduced amount of seed and fertilizer used to grow crops. As a result of these droughts, other climate-related factors, and the 2008 food price crisis, ending food stock levels of Australia, Canada, United States and the European Union fell from 47 to 27 million tonnes between 2002–2005 and 2008 (deCarbonnel, 2009).

Improved water management is implicit to the SLM approaches discussed in this report, and can best be achieved in the context of the sustainable production intensification required to increase yields, yet with the same agricultural footprints (according to physical area, environment, energy use, etc.).

2. Optimizing soil and water resource efficiency

2.1 Ecosystem processes

The complexity of ecosystems is more readily understood by considering the interactions between four basic processes: the water cycle, the mineral cycle, solar energy flow, and biological community dynamics (succession). These four processes underpin land productivity. By managing for effective and healthy ecosystem processes, SLM approaches can ensure productivity while maintaining and building ecosystem resilience.

Stages within the water cycle include evaporation, precipitation, ground infiltration, absorption by plants, and transpiration; other processes interacting with the water cycle include erosion and plant and animal production. Stages within the mineral cycle include decomposition, sedimentation, the formation of rocks and fossil fuels, combustion, metabolization and erosion. From a biogeochemical viewpoint, energy flow comprises the vectors of (embodied) solar energy, particularly photosynthesis, and the subsequent energy and heat loss through plant and animal life cycles. Biological community dynamics, or succession, reflect the change and fluctuations over time of different species within an ecosystem, both on a cyclical and linear basis; and the interactions between those species and events. Careful observation and use of succession dynamics can yield insights and methods to achieve better results with fewer resources including energy (human and fuel). For example, in agroforestry (or reforestation) assisted natural regeneration can be achieved at around one-third of the cost of conventional reforestation. Stable ecosystems feature diverse populations above- and below the ground.

In the absence of human interference, and with appropriate human support, ecosystems are self-organizing, self-generating and self-*re*generating. Certain basic parameters must be in place in order for ecosystems to maintain and build resilience. Biological complexity is a key feature of high functioning and resilient ecosystems, as well as a pillar for sustainable production intensification (SPI). Because it allows increases in production on the same ecological footprint, SPI is being taken up with particular success in the context of developing countries (Pretty *et al*., 2006).

2.2 Ecosystem services

Diversification of farm income includes compensating producers to maintain and improve soil and water health and biological diversity, as a result of the direct or indirect socio-economic and environmental benefits these bring. The concept of ecosystem services offers a conceptual means to understand the benefits provided by ecosystem processes and a practical means to bolster them. Ecosystem processes underpin ecosystem services.

In 1997 Costanza *et al*. estimated the value of ecosystem services provided to humanity by nature 'for free' every year at US$33 trillion, almost double the combined global GDP at the time. The development of markets for ecosystem services can offer urgently needed incentive pathways towards the replacement of cost-benefit accounting methods that externalize costs with full-cost environmental accounting. This broader transition will be necessary to replace perverse incentives with a level decision-making and implementation playing field that would inevitably lead to more sustainable outcomes.

Among the many ecosystem services associated with transitions to SLM systems are the regulating of soil and air temperatures, mitigation of soil degradation, reduced dust load in the atmosphere, improved water quality, aquifer recharge through improved infiltration and soil water holding capacity, decreased risk of flooding and drought, increased biological diversity, increased pollination, and improved habitat for humans and wildlife.

Use of SLM practices means that activities of producers benefit ecosystems, whether those benefits are fully recognized and/or monetized or not. Where it has been understood that such benefits translate to avoided costs or added value for the private and/or public sectors, there is the potential to compensate producers for maintaining environmentally benign practices. This approach is particularly important where these payments can defray or exceed the short-term financial gain that would accrue to producers from unsustainable practices such as deforestation.

Early examples of payments for ecosystem services (PES) include farmers located close to or upstream from water processing and bottling plants being paid to maintain sustainable practices. This is a cheaper and more satisfying solution for the enterprises involved than high-tech chemical treatments. Terrestrial carbon sequestration in soils and trees is considered an ecosystem service, and one that will likely open the door to the monetization of many others, because of the many contributions of biocarbon to the functioning of ecosystems.

However many different ecosystem services are ultimately monetized, producers can be supported in the implementation and maintenance of these services through a variety of public-, private-, and public-private mechanisms, including tax credits, eco-labelling, ecotourism, environmentally-friendly Fair Trade, rural-urban reciprocal programmes and responsible stewardship awards funded from governmental sources.

Payment for ecosystem services, associated with carbon sequestration and sustainable manure management, may provide critical economic tools to break the downward cycle of nutrient mining, soil degradation, declining yields and poverty. PES can aid the transition to sustainable agriculture by representing the internalization of previously externalized environmental, social and financial costs.

2.3 The role of soil organic carbon in ecosystem processes and services

Soil organic carbon (SOC) forms 50 percent of soil organic matter (SOM). Because of its central role in soil health and ecosystem stability and regeneration, SOC forms the foundation of ecosystem functions. For example, SOC is the primary repository of soil fertility, an indicator of soil structure, cation exchange, nutrient cycling, water holding capacity and carbon sequestration (FAO, 2008). Soil organic carbon denatures toxins, immobilizes pollutants and buffers soil temperature and various changes in soil water and hydrology: these factors are crucial to plant growth.

The benefits from increasing SOC content can be classified according to those that directly affect soil health, as well as those with wider benefits pertaining to agriculture, climate and society. Because of the need to retain or replace SOC, optimized retention of crop residues, manure and other organic material within the production system, are critical criteria for sustainable land management.

2.4 Assessing ecological impact

The concept of the **ecological footprint** dates to the work of Wackernegel and Rees at the University of British Columbia in the 1990s. Originally the term was used to describe the 'ecological' footprint of a defined human population or economy. The usefulness and popularity of the concept has since led to its use in more specific ways.

A footprint can be defined as an accounting for the (net) effect of a product, process, system, individual, organization, population or economy (item/actor), concerning a wide number of factors and areas of ecological impact, including water use, water quality, energy use and GHG emissions. Any way in which an entity can affect any aspect of a natural system or natural resource (tangible or intangible) can represent a different kind of footprint, which, in line with the original sense of the word, is a mark that human presence or activity leaves on a natural environment.

These conceptual tools allow ready discussion of the complex interrelated dynamics between changes and effects in different areas. The more precise the quantification of each respective footprint, provided it is based on accurate and obtainable parameters, the more useful that measure or metric is when it comes to making comparisons between one scenario and another.

A Life Cycle Analysis (LCA) is used to accurately quantify the footprint(s) of a unit of product, and in the case of agriculture, a commodity (e.g. kilograms of milk). The LCA includes a methodology that accounts for the component effects and net effect — on and off farm — of the product according to its different environmental effects. Like footprints, use of LCAs helps bridge the gap between past frameworks, based on monofactorial thinking, and the systems thinking that is appropriate for understanding complex natural and anthropogenic systems.

The LCAs tend to be data intensive and successful use depends upon:

- determining very clear and comparable boundaries to LCA accounting according to data accuracy;
- understanding the parameters for LCA data and findings, *especially when making comparisons* with other products, services and processes; and
- ensuring that required data are obtainable, in practical and financial terms.

When assessing agricultural impact on the environment, it is important to both consider impacts per unit of product and to understand the overall farming system or landscape level budget. While LCAs can provide information on a given value chain, farms themselves may represent a high degree of integration, and overall may be enhancing environmental services and serving as a net carbon sink.

3. Current status of the management of agro-ecosystems

Over the last decade there has been a strong trend towards taking an **ecosystem approach** to land management. This strategy for integrated and sustainable management of land, water and biological recognizes humans and their requirements and actions as integral to ecosystems. There has also been increasing adoption of **eco-agriculture,** which facilitates the convergence of agriculture, biodiversity and the stabilisation of rural livelihoods by recognizing producers and communities as stewards of biodiverse agriculture. A third trend has been **management at the landscape scale**, which takes into account the actors and stakeholders (human and otherwise) within a landscape, for example a watershed; considers their rights, needs, desires and goals; and develops balanced and integrated solutions that lead to enhanced ecosystem function (IUCN, 2008; McNeely and Scherr, 2003).

Landscapes are best delineated functionally, and thus provide a focal point for stakeholder planning and the integrated management of resources, based on local ecological (land, water and biodiversity) and socio-economic conditions (Buck *et al*., 2006; FAO, 2010a). Productive landscapes that provide biodiversity, food, water and other forms of livelihood are inherently complex systems (Buck and Scherr, 2009).

Eco-agriculture emphasizes landscape ecosystem resilience where landscape management is composed both of agro-ecological practices and modified conventional practices that make agricultural production more ecosystem friendly; and of ecosystem management practices that are more beneficial to agricultural producers within the same landscape mosaic (Buck *et al*., 2006; UNDP, 1995). Climate change is likely to add further momentum to these trends as countries gear up for greener economies and seek to shorten food chains while promoting food and nutrition security.

Behind these approaches has been the evolution of **agro-ecology** as a science and practice. *Agro-ecology is the application of ecological concepts and principles to the design and management of sustainable agro-ecosystems* (FAO, 2007b). Agro-ecology is alternatively defined as *the ecology of food systems, or the marriage of ecology and agriculture* (Francis *et al*., 2006). Agro-ecology (AE) takes a whole-systems approach to agriculture and food systems, with methods sourced from both traditional agriculture and modern innovations, with an emphasis on local food production and systems.

Agro-ecological principles encompass aspects of different SLM approaches without being limited to any particular approach, but they employ the ecological and social dimensions of traditional farming (FAO, 2007b). Agro-ecological methods are directly relevant to sustainable use of soil, water and energy resources and result in the more harmonious interaction of agriculture and ecology. Agro-ecological systems can be assessed based on *productivity, stability, sustainability* and *equitability*, viewing these properties as interconnected. Thus the aspects of farmer control, low cost of implementation, and the focus on small landowners, are as important as the biological aspects.

Features of agro-ecology at the farm and landscape level include (FAO, 2008):

- replacing manufactured inputs with natural inputs and ecological processes;
- recycling local resources;
- minimizing or eliminating tillage;
- optimizing biomass production and increasing SOM;
- increasing biodiversity of crop, plant, animal and soil biota;
- diversifying farm structure;
- re-establishing and enhancing natural biological relationships and processes;
- promoting soil biological activity, to maintain and enhance soil fertility; and
- maintaining a complex agro-ecosystem to provide ecosystem services and resilience.

These are met through practices such as crop rotations, relay cropping, intercropping, polycultures, incorporating multifunctional trees, agroforestry, crop-livestock integration and aquaculture (FAO, 2008). Agro-ecology also uses nitrogen-fixing cover crops, mulches and perennials, and renewable sources of energy; employs rotational grazing, intercropping, intra-species variety and seed saving, pest management rather than 'control'; encourages beneficial insects and biota including mycorrhizae; minimizes impacts on neighbouring ecosystems; conserves resources including energy and soil nutrients, and water through dry farming and efficient irrigation; maintains local landraces and heirloom varieties, and undisturbed areas as buffer zones; returns crop residues to the soil. (FAO, 2007b; FAO, 2008; Altieri and Koohafkan, 2008)

Sustainable production intensification is viewed as a means to increase production sustainably in preparation for feeding a greater population on the current resource base. Sustainable production intensification is based upon:

- Synergistic solutions that incorporate a high degree of diversification, with crop and animal processes interlaced in space and function. This optimizes efficiencies regarding inputs, yields, energy and time. Integration of elements reduces the area footprint needed for operations.

- Conservation of nutrients, which often cycle through the farm system many times before leaving it. This 'on-site reinvestment' approach to resource spending means that each cycle represents, in addition to yields, a nutrient processing stage to provide inputs for the next cycle within the system.

- Taking advantage of local knowledge and ecosystem specificities that the smallholder farmer is uniquely positioned to observe and implement (Perfecto and Vandermeer, 2010). Industrial agriculture ignores these peculiarities, missing opportunities and exacerbating sensitive areas. Some opportunities are not pre-existing but develop in the context of a maturing biodiverse production system.

4. Sustainable land management

By removing constraints to ecosystem self-regeneration, production systems that encourage sustainable use of soil and water resources and enhance biological diversity positively affect the provision of natural resources. These systems, practices and approaches come under the umbrella of SLM approaches and represent qualitative changes in management (FAO, 2007b). They generally cause reductions in energy expenditure and GHG emissions, compared to business as usual scenarios.

With SLM, water and nutrients are retained longer within the system; above- and below ground biodiversity is enhanced, as is nutrient cycling, in ways that influence productivity directly and indirectly. Application of SLM approaches, compared to conventional approaches, leads to increased terrestrial carbon sequestration in soils and biomass, and can foster relative oases of biodiversity, complexity and resilience. In addition, SLM approaches can use significantly less energy and represents decreased GHG emissions for example by minimizing use of synthetic inputs, which rely on fuel intensive manufacturing processes.

Some common features of SLM include:

- greater resource efficiency, through waste reduction, on-site retention and recycling of nutrients;

- use of natural processes in lieu of artificial imports;

- maintaining soil cover, increasing soil tilth, water infiltration and water retention;

- complex interrelated or layered components within the system;

- Improved functioning of ecosystem processes;

- benefiting from traditional agriculture, with modern innovations; and

- reduced or eliminated use of synthetic substances (which tend to come with high environmental price tags and are subject to fluctuations in commodity prices).

SLM is not a single set of practices. The umbrella of sustainable agro-ecology contains a number of congruent approaches that encompass myriad technologies, systems and know-how that are appropriate according to different scales, regions, and agro-ecological zones. Because of the evolution of different practices and production systems, overlap of the approaches featured is unavoidable, particularly concerning the elements within them (e.g. maximizing crop residue, enhancing nutrient and water cycles, etc.). As a specific example, the use of leguminous 'fertilizer trees' are integrated into conservation agriculture, agroforestry and permaculture. Users and developers of different production systems are continually seeking greater efficiencies and increased yield-to-cost/input ratios. Emerging innovations tend to borrow and synthesize the best elements from elsewhere.

Challenges associated with sustainable production systems

The specific approaches discussed in the report represent a number of identified best practices meant to enhance productivity and build the resilience of ecosystems. However, each has its potential technical, labour or productivity drawbacks depending on the context as well potential socio-economic or political constraints that inhibit wide spread adoption.

For example, tillage or ploughing has historically been and is still a widespread practice – its benefits are considered to be the breaking of crusts and hardpans for water and root infiltration, controlling weeds and pests, incorporating fertilizers and ensuring ease of seed germination, among others. In the case of organic agriculture, tillage is often used to avoid the use of synthetic pesticides. However, tillage diminishes the build up of organic matter, releasing CO_2 into the atmosphere and reducing available nutrients and increasing the potential for soil erosion. Tillage can be highly labour-intensive depending on the available equipment. Conservation agriculture on the other hand can lead to initial drops in yield, requires access to equipment planting and is subject to competition (particularly for animal feeds) for the crop residues left on the soil surface, which are a critical component for soil cover and moisture retention.

A ubiquitous social issue associated with the adoption of sustainable practices is related to gender. While men and women are similarly efficient as farmers (Quisumbing, 1995), most of the world's farmers are women who carry out the majority of farming activities in developing countries. A number of constraints limit women's ability to contribute to farm decisions. These may be techno-institutional constraints, such as lack of extension programmes or access to, or awareness about non-governmental organization (NGO) programmes for women. They may also be insufficiently aware of farm credit sources, or there may be socio-personal constraints (e.g. misconceptions that women farmers do not have farming ideas, women's low self-esteem).

Economic/financial constraints also include low or lack of financial contributions to farming activities and access to credit support groups such as co-operatives, as well as the unwillingness of women to invest in a male-dominated farming environment, such as cocoa (Enete and Amusa, 2010). Lack of critical services, e.g. extension and credit are key among the major constraints to adoption for both men and women. Education of women has been shown to increase technology uptake, significantly through peer-to-peer influence. An additional year of education for women can lead to yield increases of 2 to 15 percent (Quisumbing, 1995).

A key dilemma facing the success of capacity development in agriculture is that while women are key players, men still continue to make the decisions (Enete and Amusa, 2010).

4.1 Different sustainable land management approaches

SLM approaches include conservation agriculture, agro-ecology, eco-agriculture complemented by integrated pest management, and elements of agroforestry, traditional agriculture, organic agriculture, permaculture and certain intensive and extensive livestock-oriented systems; including pastoral and integrated crop-livestock systems. SLM resource-saving technologies and practices include aquaculture and water harvesting (Pretty, 2009). Different scenarios suggest the selection of different combinations of SLM approaches, or hybrid solutions. Many SLM solutions will benefit from the study of local traditional agricultural practices.

SLM systems allow for innovative combinations of practices and even approaches to provide even greater resource efficiencies, system component interdependence, biodiversity, yields and diversification.

Conservation agriculture

In response to declining yields, in the twentieth century farmers and scientists developed methods to preserve and build soil and SOM while maintaining or increasing yields. Conservation agriculture (CA) is a set of interacting agricultural practices that combine profitable agricultural production with environmental improvement (FAO, 2007a). The objective of CA is “to improve agricultural production by adopting economically, ecologically and socially sustainable methods.” (FAO, No Date.) CA is grouped around three core principles that, applied simultaneously, provide a basis for sustainability because of their synergetic effects: minimal soil disturbance, permanent soil cover and crop diversity. Crop residues are left in place on the soil surface after harvest, not turned into the soil, burned, or harvested for a secondary crop. This improves soil structure, with decomposing residues opening up soil pore spaces. SOM then builds up over time (Franzluebbers, 2007). There are now around 116 million ha under CA worldwide.

Established CA systems provide the following benefits, among others: improved rainwater infiltration, soil structure, water-holding capacity and environment for root development, and air quality: reduced evaporation, soil compaction – if complemented with suitable measures such as controlled traffic farming, water erosion, runoff and associated losses of soil, water, seeds, inputs and SOM; increased biodiversity; reduced wind erosion and day-night temperature differences; reductions in labour, synthetic fertilizer, pesticide and fossil fuel use; and reduced production costs, higher yields, higher profit margins and lower peak labour demands. All of these benefits have knock-on socio-economic benefits (FAO, 2007a; FAO, 2008; FAO, 2006b; Franzluebbers, 2007).

Intensive tillage destroys essential soil biota, and leads to erosion by wind and water. The machinery and equipment used for tillage compacts soils, decreasing productivity, tilth and soil biodiversity. Tillage leads to rapid declines in SOM stocks, especially in hot and arid regions (FAO, 2008). Soils can lose 50 percent of SOC content within 20 years of cultivation (Kinsella, 1995), or as much as 40 percent in the tropics within six years following deforestation (FAO, 2008, citing Wood *et al.*, 2000). Avoiding mechanical soil tillage is essential to maintaining soil minerals, preventing erosion and improving water use efficiency. Instead of mechanical tillage, ‘biological tillage’ maintains soil aeration, with structure and tilth supported by soil fauna and micro-organisms within stable agro-ecosystems, in the absence of compaction and resource inefficiency (FAO, 2008).

CA excludes mechanical soil tillage as periodic soil structuring operation. It includes no-till, and some form of strip or zone tillage methods where applicable. These methods vary according to the degree of associated soil disturbance; even with no-till the ground is opened for seeding by coulters, row cleaners, disc openers, in-row chisels or strip-rototillers with different degrees of soil disturbance (NCSU, 2001). Strip tillage involves disturbing a narrow strip of soil just wide enough to deposit seed or seedlings. This is a good solution for eroded soils where pre-existing compaction outside the strip disadvantages weeds (NCSU, 2001) or where cold and moist soil conditions delay crop emergence in spring time. Crop rotation prevents soil nutrient deficiencies and loss of productivity to disease, pests and weeds, which are unable to become established for long periods of time within changing crop configurations. Crop rotation can also help build up soil tilth and health, allowing for extensive establishment of rooting zones (Hobbs *et al*., 2008).

Above the scale of the hoe farmer CA requires equipment such as no-till direct seeders and planters. A key challenge for scaling CA is the provision of necessary equipment for small-scale and resource-poor farmers in developing countries, although low-tech equipment options are available under a CA. One of the most successful programmes outside Brazil, where low-tech conservation farming has been pioneered, is in Zambia, where 120 000 Zambian farmers have benefited, and by 2011 the programme will have served 250 000 families, or 30 percent of Zambia's farming community (CFU, 2010).

Conservation agriculture can readily be integrated with and complemented by other SLM approaches and practices, such as agroforestry, IPM, IPNM and ICLS. Conservation agriculture with trees incorporates their use to enrich soils and provide fodder for animals. In particular *Faidherbia albida* is used to take advantage of its nitrogen-rich leaf fall during the growing season, a feature of its unique reverse phenology.

Because of its proven track record, CA is now being promoted by FAO in developing and emerging economies, as are many other SLM systems and approaches. Sub-Saharan Africa is a critical test case for SLM methods because of the extreme and urgent degradation occurring and compounding health and conflict issues. If problems in SSA can be solved, then the global prognosis for SLM and sustainable production intensification is certainly promising. The success of the Zambian programme has led FAO to scale-up the programme throughout the COMESA region. Other regions with strong growth rates in the adoption of CA are Central (Kazakhstan) and East Asia (China), the south Cone of Latin America, Canada and Australia.

Organic agriculture

Organic agriculture is defined by the Codex Alimentarius Commission as "a holistic production management system that avoids use of synthetic fertilizers, pesticides and genetically modified organisms, minimizes pollution of air, soil and water, and optimizes the health and productivity of interdependent communities of plants, animals and people." (FAO, 2001)

Organic agriculture contributes to sustainable diversification of rural economies while supporting and increasing the function of ecosystems and the stability of the natural resource base. Over 32 million ha worldwide are now farmed organically by 1.2 million farmers with organic wild products harvested on an additional 30 million ha. Organic agriculture systems are characterized by resource efficiency, low external inputs and improved SOM levels. SOM is the key indicator for soil–water retention and is thus critical for productivity and a healthy water cycle. Like other SLM approaches, organic agriculture developed from a response to the hyper-industrialization of agriculture and the associated externalization of environmental costs.

Organic farming comprises sustainable crop and animal production systems, methods and technologies that enhance environmental stability and food security. Organic food systems are governed by recognized standards at the national and international level (Francis *et al*., 2006); although there is considerable variation in certification standards, development of which began in the 1980s.

Benefits of organic agriculture, compared to conventional production, include: reuse of livestock waste reduces pollution and increases production; increased above- and below ground biomass improves biodiversity, aiding biological pest control and increasing crop pollination by insects; yields that equal those from conventional agriculture; higher per unit sale prices for organic products means that net economic return per hectare can equal or surpass that for conventionally grown crops; and labour inputs are often higher in organic systems, but more evenly distributed through the year; on the other hand, work is freer from the risk of chemical contamination (Pimentel *et al*., 2005).

Organic practices include:

- rotational cropping, conserving soil and water resources, and reducing insect, weed, pest, and disease problems;
- legume-based intercropping;
- (off season) cover cropping;
- conservation and building of SOM (using covered soils, compost, green manures and mulch);
- mechanical cultivation;
- biological pest control (as for IPM and permaculture); and
- using natural biodiversity to replace the chemical action of nitrogen fertilizers, herbicides, insecticides, and fungicides.

By now a highly capitalized and mainstream organic food and fibre industry, driven by burgeoning demand in developed countries, and overlapping with Fair Trade, has begun to shift the global agricultural landscape. Ideological battles concerning the exact merits of organic agriculture are of secondary importance to the opportunities provided to producers and agro-ecosystems. Organic farming in some instances can provide pathways out of poverty for producers in the developing world. Besides the organic export sector, in developing countries many uncertified smallholder properties are farmed organically on a subsistence basis (Müller-Lindenlauf/FAO, 2009).

One study of 37 million ha worldwide across all eight FAO-classified production system types found that transitions to traditional and organic methods provided an average 79.2 percent increase in yield against previous yields on a per project basis (Pretty *et al*., 2006).

Traditional agriculture

Traditional agriculture comprises indigenous forms of ecological agriculture that result from the co-evolution of social and environmental systems, in the absence of external inputs, capital, or modern scientific knowledge (Altieri, No Date). Centuries of trial and error, self-reliance and intuitive processes, coupled with a deep understanding of local ecosystems, have provided producers with large agro-ecological knowledge banks that allow locally available resources to be managed in specific ways that promote biodiversity, community food security and socio-agricultural stability. Very specific use of environmental knowledge and natural resources results in complex interfaces between productive and natural systems. Careful management of these systems can result in higher, or at least more sustainable yields than conventional agriculture. Traditional agriculture is characterized by a high degree of complexity and plant biodiversity. The diversified production base provided by many traditional systems is critical for the diet of many farming families.

Not all traditional methods are sustainable in a modern context (e.g. slash-and-burn); on the other hand, many apparently traditional practices, such as ploughing in Africa, are not traditional methods at all but imported from Europe during the Nineteenth Century or even before. The unsustainability of these methods can hardly be wondered at. Such systems will benefit from updating or replacement with successful polycultural methods; solutions are available from both recent and more long-standing innovations.

For the purpose of this report, *traditional agriculture* refers to forms of agriculture that are by implication sustainable in at least some modern contexts. Some such forms have been developed in developed nations. For example, despite receiving less than 150 mm precipitation per year, the Spanish island of Lanzarote produces a renowned wine. Vines are planted in conical hollows that are filled with volcanic ash and lava stones; these basins retain eight times more water than bare soils (IRD, 2008).

Traditional and organic agriculture can produce yields comparable or higher than conventional agriculture (Stanhill, 1990; Badgley *et al*., 2007; Pimentel *et al*., 2005; Naerstad, 2007; UNCTAD-UNEP, 2008; Uphoff, 2003). Beyond even the concept of synergistic benefits, traditional systems are often comprised of the interdependent elements forming a whole that would not function in the absence of even one component system. This is the case for mulberry dyke systems in southern China that combine market gardening, aquaculture, and mulberry plants for silk worms (IRD, 2008).

Traditional agriculture also supports diversity outside cultivated areas. Wild gathering fishing and hunting provide further diversity benefits in terms of resilience, diet and reduced stress on the principal productive systems (FAO, 2008). In Latin America alone there are 2.5 million acres (1 acre = 4.05 ha) under traditional polycultures. Home gardens in the region incorporate a wide variety of crops with different habits, each using a particular solar/nutrient niche in symbiosis with surrounding species, particularly in regard to access to sunlight.

Heterogeneous traditional systems still cover 5 million ha worldwide, some of which are exemplified in the Globally Important Agricultural Heritage Sites (GIAHS), an FAO initiative that highlights traditional models of agriculture that support agrobiodiversity and year-round yields without overuse of agrochemicals. Those GIAHS with a proven ability to sustain relatively dense human populations provide clues to help solve critical current challenges such as sustainable production intensification and climate change.

Traditional agriculture encompasses a wide variety of agricultural system designs. The reason for this diversity is that each system has been honed over centuries for the precise agroclimatic conditions in which it evolved. Despite this diversity, there sometimes appear striking similarities across systems from different regions and continents, in response to similar environmental constraints and production opportunities. For example in marshy areas there are similarities between forms of raised field agriculture: *Mexican chinampas, Andean camellones*, the *hortillonages* of Europe and Asia, and the drained taro fields of the western Pacific; all involve canal networks and raised plots of land (IRD, 2008).

The commercial success of traditional sustainable methods in developing countries today, notably in Asia, where applicable establishes their potential within programmes for the sustainable production intensification (SPI) that is needed to meet pressing food and environmental needs.

Traditional systems offer solutions to challenges facing agriculture today. For example, a potential stratagem in the era of climate change comes from Andean mountain agriculture, where farmers manage plots in different agroclimatic zones to hedge against unpredictable weather and crop failure. This approach may be replicated and developed for high-impact/high-risk agricultural areas in the front line of climate change.

Agroforestry

Agroforestry is a form of SLM that represents the intentional integration of woody perennials with crops and/or livestock to access the beneficial interactions between these elements. Agroforesty balances ecological needs with the sustainable and profitable harvesting of tree and forest resources. Crops and woody species are integrated spatially or over time. There are thus two types of agroforestry system: simultaneous and sequential.

The wide variety of viable products within agroforestry systems and effective use of the vertical dimension means that agroforestry (AF) systems are viable on restricted area footprints. AF greatly improves the nutritional balance of producer family diets, compared to conventional alternative systems. Knowledge of the positive interactions between species and any contraindicated combinations is essential, as is true for all integrated modalities. Tropical agroforestry systems are often used as an example of traditional agriculture polycultures, containing more than 100 plant species per field, which are used for construction, firewood, tools, medicines, livestock feed, and human food (Altieri, No date).

Interest in agroforestry has grown in recent decades because of, *inter alia*: tropical deforestation, economic hardship in developing countries, population-driven land degradation and land scarcity and growing interest in agro-ecological farming systems (Woodfine, 2009). Agroforestry increases carbon sequestration, if combined with conservation agriculture or silvopastoral systems, in both soils and biomass. By using forest systems, the fertile 'forest edge', and in open spaces planted with trees, agroforestry has unique positive effects on yield, ecosystem complexity and resilience. Agroforestry elements are peppered throughout different SLM approaches, and with good reason: the combination of trees and medium- and low-height crops control erosion, build soil fertility, enhance species diversity and solar energy capture, among other benefits.

The World Agroforestry Centre (ICRAF) is now leading an alliance of government, donors, research and development partners in promoting Evergreen Agriculture in Africa. Evergreen Agriculture capitalizes on best practices by integrating tree species (such as *Faidherbia albida* discussed above) into food systems (crop and livestock), resulting in sustained green cover on the land, higher biomass production and enhanced soil fertility. It enables farmers by providing them with practical ways to reduce soil tillage, improve the efficiency of rainwater use, increase soil carbon accumulation and improve soil health. Evergreen Agriculture is practiced in a number of countries in East, Southern and West Africa. In Malawi alone 500 000 farmers have integrated fertilizer trees into their production systems. Currently the Ministers of Agriculture and Environment across Africa have endorsed a recommendation to scale-up these practices, and COMESA will be investing US$50 million in these systems over the next five years (Garrity *et al*., 2010 in press).

There are five principal forms of agroforestry identified in the literature: **alley cropping, forest farming, silvopastoralism, riparian forest buffers and windbreaks.** Common to all forms of AF are the principles of Intentional, Integrated, Intensive and Interactive management.

Alley cropping is a form of intercropping whereby trees are introduced to productive land and crops are planted between them. This arrangement creates beneficial microclimates, retains soil moisture, increases pollination and biodiversity, provides shade, windbreaks, and prevents erosion. Tree and plant crops species are carefully selected to ensure compatibility and optimize synergies.

Forest farming is the integrated cultivation of high-value non-timber species under forest canopies that are optimized for shade, thus providing diversified income while high-quality trees are being grown for wood products. Non-timber crops fall under the categories of food (mushrooms, fruit and nuts), botanical and medicinal plants, bee products, decorative products, floral crops and handicrafts (USDA, 1997; Cornell University, 2002). Whereas alley cropping and silvopastoralism introduce trees into agricultural systems, forest farming sees the introduction of cropping techniques into existing forest systems. Forest farming can provide short-term income from existing lots with minimum capital outlay (Woodfine, 2009), providing critical opportunities for producers to improve their economic situations. **Silvopastoralism** includes the introduction of trees to grazing areas, providing shade and shelter, increased resilience, and in some cases improved forage quality. Increasing the number of trees in rangelands provides fuelwood and can improve SOC/SOM levels. Competition between trees and plants is reduced by selecting plants with different root depths or those that grow at different times of the year (USDA, 1997). Leguminous trees improve soil physical properties through increased root nodule microbial activity, nitrogen fixation and biomass incorporated into the soil (Woodfine, 2009).

Silvopastoralism can bring abut dramatic results: 20 years ago in the Shinyanga region of Tanzania soil erosion was such that dust storms were common; today the activity of the Shinyanga Land Rehabilitation Programme (HASHI) means that woodlots yield firewood and building timber, while fruit orchards provide food, and fodder trees supply protein-rich feed for livestock. Rice production has been tripled on the same area of land. Profits allow producers to obtain land, pay for medical care and school fees for their children.

Assisted natural regeneration, the process of using natural succession to establish forest stands, and temporary closures, are comparatively low-cost ways to establish new stands or woodlots (Woodfine, 2009).

Riparian forest buffers comprise trees and shrubs near streams, lakes, ponds, and wetlands, and include a wide variety of tree and shrub species (native where possible). As part of integrated riparian management, these buffers enhance and protect aquatic and riparian resources, as well as provide ecosystem services including improved water quality, water temperature buffering, water filtration and sediment reduction.

Windbreaks composed of trees and shrubs are planted to protect crops, people and livestock from winds. Field windbreaks protect wind-sensitive crops, control wind erosion, and increase bee pollination and pesticide effectiveness. Livestock windbreaks reduce animal stress and mortality, reduce feed consumption, visual impacts and odours.

Agroforestry practices also include fallows, home gardens, growing annual agricultural crops during the establishment of a forestry plantation (*taungya*), growing multipurpose trees and shrubs on farmland, boundary planting, farm woodlots, orchards or tree gardens, plantation/crop combinations, shelterbelts, conservation hedges, fodder banks, live fences, growing trees on pasture and apiculture with trees (Woodfine 2009, citing FAO, 2005).

Sustainable pasture and rangeland improvement

The livestock sector provides livelihoods to 1.3 billion people, mostly smallholder farmers and pastoralists in the developing world. For 200 million people grazing livestock is the only viable form of livelihood (FAO, No date), and livestock production is the only viable form of agriculture in most areas of rangeland, grassland and pasture because these areas are too dry, wet, cold or high for cropping (van t'Hooft, 2009). Grazing livestock allows the conversion of low-quality biomass into high-quality agricultural products.

Grasslands represent up to 70 percent of global agriculture area. The world's 3.4 billion ha of rangelands hold up to 20 percent of the world's soil carbon (Neely *et al*., 2009); however the majority of these areas are affected by some degree of soil degradation. This associated historical loss of soil organic matter indicates the potential capacity of this carbon sink.

Sustainable land management practices for pasture and rangeland improve the capture, infiltration and storage of rainwater in soils, supporting the conditions that increase SOC/SOM, vegetation and biodiversity (Woodfine, 2009). There is congruence between sustainable livestock practices and those for soil carbon sequestration, which include restoring organic matter to soils, reducing erosion, and decreasing losses from burning and inappropriate grazing practices (Neely *et al*., 2009).

Rapidly increasing demand for livestock products means that there will be significant negative consequences if the production footprint of livestock does not significantly decrease. This is an urgent rationale for approaches such as sustainable grazing land management or integrated crop-livestock-tree systems (ICLS), in which crop residues provide feed for livestock, which in turn produce manure to fertilize crops, within on-site or in-landscape nutrient cycling. Productive systems that concur with ecosystem cycles gain the stability and resilience of those systems. Climates that can produce crops year-round are ideally suited to ICLS (Franzluebbers, 2007), and once stability is secured, can produce far-higher yields.

Although they have been a feature of traditional agriculture for centuries, ICLS are now benefiting from synergistic components provided by the modern crop, livestock and agroforestry sectors. ICLS positively affect biodiversity, soil health, ecosystem services, forest preservation, and adaptation to and mitigation of climate change. Variants include systems with or without trees or aquaculture, and agropastoral systems with or without trees. Cropping based on conservation agriculture methods allows cropping to be integrated with other land uses and for the shift from crops to pasture to be managed without soil tillage, which is interruptive and unsustainable.

Irrigation of pasture has a large environmental and GHG footprint, yet provides significantly increased yields. From an environmental viewpoint pasture is often vastly preferable to feedlot operations that concentrate production to a maximum degree, not only creating hotspots owing to the concentration of cattle activity, but also importing cereal-based feed products that diverts land use from human provision. Feedlots have a massive energy/water/GHG footprint and must be viewed through a systems lens to be improved.

Transitions to more sustainable pasture management will see adjustments, *inter alia*, in irrigation water uptake, delivery (including time of day), selection of different grass cultivars for lower evapotranspiration and improved nutritional content (leading to lower *biomass: product* ratios), and complementary use of rangeland grazing. Implementing different SLM changes together is preferable and sometimes essential for success. It is in the developing world that change will have the greatest effect on the lives of producers, land degradation and rural economies.

Livestock have important and complex cultural value in traditional cultures. Sustainable livestock management programmes should be designed and implemented with an understanding of regional cultural dynamics and sensitivity to norms and aspirations around livestock. This will be useful in optimizing the success of such programmes.

Pasture cropping, developed in Australia and now popular in many other countries including Brazil, combines cropping and grazing into one land management technique that benefits both uses. Winter and summer crops can be grown without destroying the perennial pasture base. The ground is never ploughed. Instead crops are sown into existing pasture; this stimulates perennial seedlings in a beneficial way, and radically reduces input and cropping costs. One field yielded 2.5 tonnes/ha of oats, having been grazed twice in the same year (Seis, 2006). In Australia, use of native perennial grass species has been found to provide the best results. Weeds are controlled using thick litter layers by using appropriate grazing management. There are now over 1 500 pasture croppers in Australia, where the technique began in the 1990s. This system has achieved a doubling of soil carbon levels from 2 to 4 percent over ten years, which is made possible with conservation agriculture principles.

Holistic grazing strategies

It is not the presence or absence of livestock but the choice of grazing management system, and its suitability for the landscape, that leads to positive or negative effects (see Figure 1). In recent decades grassland management systems have been developed that not only reduce the impacts of grazing but also use livestock as a tool to enhance productivity and ecosystem function. The best known of these is Holistic Management (HM), which uses timed controlled mob grazing to replicate the behaviour and effects of wild herds of ungulates in original ecosystems. HM has been used effectively on different continents to restore grassland ecosystems in the absence of increased irrigation or rainfall.

FIGURE 1: SUSTAINABLE GRASSLAND MANAGEMENT, REQUIREMENTS AND BENEFITS (WOODFINE, 2009).

Sustainable grassland management

Requirements	Benefits
Understanding of how to use grazing to stimulate improved grass growth.	Increases the longevity of perennial grasses.
Use of the grazing process to feed livestock and soil biota.	Improves hydrology in drylands.
Maintaining 100 percent soil cover 100 percent of the time (ideally).	Helps protect and restore biodiversity.
Revitalization of natural soil forming processes.	Increases livestock productivity.
Adequate rest from grazing without over resting land areas.	Better quality and quantity of grass.
	Improved quality and quantity of meat and dairy products.

Co-evolving species come to rely on the inputs and effects of the other species. When one species group is compromised, the other suffers; the closer the symbiosis, the more stress the second group experiences. After grasses and wild ungulates co-evolved, modern settlement and agricultural patterns have interrupted their symbiotic cycles; the result is eroded and degraded landscapes, according to HM principles.

Holistic planned grazing is based on three key insights (Savory and Butterfield, 1999):

- Overgrazing is a function of the time spent grazing, not absolute animal numbers. Excluding cattle can lead to severe biodiversity loss, even soil degradation.

- Grazing lands developed in the context of historical predator-prey relationships, with ungulates herding close together and occasionally stampeding. These are the conditions under which the grasses evolved to thrive. Simulating these conditions in managed landscapes provides benefits to grass land functioning that have been absent since the destruction of the superherds.

- Land and plants respond differently to management tools depending where they are on the brittleness scale, indicative of the presence of moisture throughout the year.

Under HM, livestock graze in densities similar to those found in original environments and then moved to ungrazed areas in the same densities. After timed grazing, grass growth surpasses pre-grazing levels, above- and below ground, and can be re-grazed. Gradually grass recovery times decrease and the resilience of the grassland ecosystem is restored. HM views grazing as a tool for ecosystem regeneration, while maintaining or increasing yields, in the same way that biodiverse smallholder polycultures provide benefits outside the productive system and ecosystem services to nature. Other systems that use livestock as a land management tool are found within the repertoires of traditional agriculture, agroforestry and permaculture.

Enrichment planting

Introducing leguminous plants or trees (enrichment planting) into grazing lands increases soil nitrogen, provides ground cover and keeps soils cooler, moister, less eroded and less compacted. This allows stressed systems to recover. Trees can also be planted for fodder, or the leguminous 'fertilizer trees' can meet this need. Degraded land can also recover within exclosures, which can also be planted with leguminous species.

Fire prevention

Fire prevention is important in all the above systems because fire mineralizes essential organic matter to atmospheric CO_2. This requires special care in drylands, when dry surface residues are present, which is an important factor when saving water in these regions. Firebreaks can prevent the spread of accidental fires in forest lands. In pastures controlled burning is a strategy to reduce fire intensity, frequency and resulting damage. In cropping systems reduced burning of crop residues is a necessity for restoring soil organic matter and soil carbon and for supplementary animal feed.

Permaculture

Permaculture ('permanent agriculture' or 'permanent culture') is an ecological design system that integrates sustainable polyculture-based food production with low impact building design. Permaculture draws elements from traditional sustainable agriculture and modern innovations and principles. Permaculture systems reduce water use, improve soil quality and biodiversity, improve yields and improve diets. It includes crop-livestock systems, agroforestry methods, and methods compatible with sustainable production intensification.

Permaculture shares elements with agroforestry (forest farming, alley cropping, windbreaks), conservation agriculture (fertilizer trees, no till and uncompacted soils, permanent soil cover), organic agriculture (organic inputs and on-site nutrient recycling), traditional agriculture (rainwater harvesting and water infiltration including keyline design and tied contour bunds), sustainable livestock management (ICLS for subsistence smallholders and commercial operations) and agro-ecology (optimal selection of system elements originating in different times and places).

In developing countries, permaculture is generally used at small- and medium-scales to improve the sustainability of production and maximize community and ecosystem benefits. Although most often applied at the smallholder scale, it also includes the Keyline design system, a broadacre landscape design system that radically increases water infiltration and can remediate compacted, eroded soils. Keyline is compatible with grazing livestock and agroforestry. The keyline subsoiler introduces air into compacted soils, reduces the compaction barrier that plant roots cannot overcome, and greatly increases water infiltration and decreases bulk density.

5. Yields associated with sustainable land management approaches

Consistent and sustainable crop and livestock productivity must accompany environmental co-benefits. The data strongly suggest that while SPI is critical in ensuring increased productivity for meeting demand, SLM alone can resolve many of today's local and regional challenges related to degraded resources; an abundance of evidence (see also Badgley *et al*., 2007; Stanhill, 1990; Uphoff, 2003; Pimentel *et al*., 2005; Naerstad, 2007; UNCTAD-UNEP, 2008) suggests that ideas around the non-productivity of sustainable methods are unfounded.

In a review of 286 best practice projects in 57 countries, covering 37 million ha and representing 12.6 million farmers, with data triangulated and then independently cross-checked, Pretty *et al*. (2006) found that transitions to agro-ecological resource-saving practices led to an average yield increase of 79 percent across the eight FAO-designated production systems. These practices also improved the efficiency of water use and provided climate change mitigation and adaptation, among other benefits.

Practices and approaches surveyed included integrated pest management (IPM), integrated nutrient management (INM), conservation tillage, agroforestry, water harvesting in drylands and integrated crop-livestock systems (ICLS). Average yield changes for projects in Africa were: a 116 percent increase for all African projects and a 128 percent increase for East African projects, ranging from 54 percent in Uganda to 179 percent in Kenya. All case studies in this review also achieved increases in per hectare productivity. Furthermore, *per land unit area* yields from polycultures are approximately 20 to 60 percent higher than yields from monocultures with the same level of management (FAO, 2007b, citing UNEP, 2005).

Badgley *et al*. (2007) analysed yield ratios for organic and non-organic food worldwide and found that in developing countries organic systems produced 80 percent higher yields than conventional systems. Then, modelling global food supply on currently available land, the researchers found that today's food needs may be met using organic production methods.

There are many more examples of scientifically validated yield increases following adoption of agro-ecological or eco-agricultural practices (Parrott and Marsden, 2002; Scialabba and Hattam, 2002; Pretty and Hine, 2001; Hine and Pretty, 2008). Transitions to SLM and SPI must take place at all scales; however the focus should be on smallholders and pastoralists, because of the prevalence of widespread hunger and related constraints (FAO, 2007b).

6. Challenges and opportunities for transitioning to and scaling up SLM

Many of the constraints faced by the agricultural sector, and subsequently also in the implementation of sustainable land management practices, are multi-dimensional and fall within the purview of social, environmental, finance and trade, education and economic sectors. **Desperate circumstances** lend themselves to environmental degradation because producers in these cases are forced to make urgent and short-term decisions. On the other hand it is not enough simply to make farmers richer; without the necessary education the risk is of expanding environmentally damage (Reardon and Vosti, 2001). **Lack of capacity** and associated confidence in making wise investment decisions continues to undermine the adoption of sustainable practices. The ability to invest can be restricted owing to financial and non-financial reasons. Implementation capacity may be further limited by the availability of productive natural resources and competition for those resources.

Farmers with **insecure property rights** are unlikely to invest the resources needed to create a step change in productivity and move from subsistence to surplus. This is further hampered by depleted, overused, natural resources, such as degraded soils, that cannot support such increases without remedial measures that represent loss of income in the short-term, e.g. fallow periods. **Unstable land-use scenarios** destabilize production at a fundamental level, caused for example by encroachment and the effects of conflict. In extreme cases, which are many, the poor farmer faces a desperate choice: when to leave the land because it is unsafe to remain, even if there is nowhere else to go. **Protracted crises** remove the farmer's ability to be self-sufficient and lead to long-term food aid requirements.

Small producers, **lacking access to productive resources**, are often unable to obtain the needed credit for material investment or critical information and knowledge for putting practices in place. Often the systems of governance in place, and their failings, do not support pathways out of poverty, or worse hamper the success of farmers. Societal **power structures** are often biased against poor producers and their ability to improve their economic situation. A mentality of food security 'at any cost', either on the part of producers or embedded within the system that directs their choices, can result in environmental degradation and/or resistance to change that would improve yields and/or increase long-term viability.

Poverty and inequity create blocks to true development. When the rural poor have little purchasing power, domestic markets cannot develop (Kwa, 2001). Reardon and Vosti suggest 'investment poverty' as the key determinant in understanding the interface between poverty and environment. Investment poverty represents producers' inability to "make minimum investments in resource improvements to maintain or enhance the quantity and quality of the resource base, to forestall or reverse resource degradation" (Reardon and Vosti, 2000).

SLM requires a **qualitative shift in land management**, by removing and reducing institutional and ecosystem constraints and providing support to the requirements for transition. While many of the constraints noted above are exasperating problems that have challenged sustainability through recent history, there are numerous successful examples of improved farming and pastoral systems leading to improved livelihoods and the natural resource base.

Successful implementation of SLM depends on four principles including: land-user-driven and participatory approaches; integrated use of natural resources at ecosystem and farming systems levels; multilevel and multi-stakeholder involvement; targeted policy and institutional support, including development of incentive mechanisms for the adoption of SLM and income generation at the local level (FAO, 2010b). With climate change serving as a catalyst there will likely be greater incentive opportunities for the implementation of SLM because of the environmental co-benefits including soil carbon sequestration, water capture and holding capacity that serve the needs of mitigation and adaptation.

Transitions to sustainable agricultural practices do not always require a net decrease in inputs (Pretty, 2009); yet over time truly integrated systems generate more of their own input needs. What is of critical importance is ensuring that farmers and pastoralists play a critical role in knowledge sharing, adoption and adaptation. Farmer Field Schools (FFS) have proven invaluable for information sharing and the adoption of good practice. Farmer Field Schools are present in 80 countries and Pastoral Field Schools are being initiated.

An important step in the scaling of SLM/SPI has been the collation of databases of best practices in the literature (e.g. Pretty *et al*., 2006) offering insights into the scalability on a wider basis. The World Overview of Conservation Approaches and Technologies (WOCAT, 2010) offers in-depth analyses of SLM practices that are appropriate to different agro-ecozones and contexts.

Conversion to SLM is complex yet doable, generally requiring a landscape approach (Pretty, 2009). Interactions between agro-ecosystems of farms and surrounding farm or non-farm systems need to be developed (Pretty, 2007). At regional and national levels, a cue can be taken from WRI’s relational mapping of human and environmental factors in Kenya (WRI *et al*., 2007).

Regional maps can be developed with layers for different parameters including: land degradation, historic production levels, land use and crop production, historic land-use changes, SOC/SOM levels, precipitation, predicted effects of climate change, human population factors, wildlife populations, growing season, temperature, tribal boundaries and producer access to capital. A layer can be superimposed over these with recommended and SLM/SPI approaches. This format can help optimize environmental and socio-economic benefits from SLM/SPI programmes, and associated efficiency of funding resources.

The above tools and processes can be used to prepare for assess to and aid in the development of terrestrial carbon sequestration projects such as REDD/REDD+/REDD++; and Payments for Ecosystem Services projects. These resources should be taken online once ready to amplify accessibility, benefits and horizontal communication.

7. Conclusions and way forward

While the interconnectedness of globalized systems has brought extreme challenges to producers and the environment, particularly in the context of developing countries, this deep interrelation also provides unique opportunities. Agriculture is at the nexus of convergent world crises. A major transition to sustainable agriculture will prove to be catalytic for solutions beyond the agricultural sector. Cross-sectoral approaches that allow for agriculture and the environment to be better integrated are critical to mainstreaming sustainable practices.

However, greater recognition is required of the fact that SLM and SPI can offer improved livelihoods (income, food security, education) while maintaining the foundation natural resource base.

Management systems needed to optimize the sustainability of agriculture worldwide are available today, and have proven yields. With the myriad of promising approaches available, the focus for future activities must be on removing constraints to adoption while strengthening the implementation capacity of farmers and pastoralists. Wider adoption and scaling should include embracing complex systems, a fully participatory process, bridging mechanisms and support networks allowing for biodiverse agro-ecosystems and sustainable food producing landscapes to become established. All of these will necessarily play out against a background of the unpredictable impacts of climate change and economic forces.

Given the multiple and converging crises, sustainable production intensification and sustainable land management offer ready responses to meeting human demands for food security and livelihoods while maintaining and preserving the environment.

8. References

Altieri, M. A. & Koohafkan, P. 2008. Enduring farms: *Climate change, smallholders and traditional farming communities.* Penang, Malaysia, Third World Network.

Altieri, M.A. No date. Traditional agriculture, (Available at: http://www.cnr.berkeley.edu/~christos/articles/traditional_ag.html. Accessed June 2, 2010).

Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Chappell, M.J., Avilés-Vázquez, K., Samulon, A. & Perfecto, I. 2007. *Renewable agriculture and food systems*, 22: 86-108.

Buck, L. E. & Scherr, S.J. 2009. Building innovation systems for managing complex landscapes. In K. Moore (ed) *Innovating for sustainable agriculture and natural resource management: The science of adaptive management.* Soil and Water Conservation Society.

Buck, L. E., Milder, J. C., Gavin, T. A. & Mukherjee, I. 2006. *Understanding ecoagriculture: a framework for measuring landscape performance.* Discussion Paper number 2, Sep 2006. Washington, DC, Ecoagriculture Partners.

Conservation Farming Unit. 2010. (Web site: http://www.conservationagriculture.org). Accessed June 2010.

Cornell University. 2002. Agroforestry learning communities in the Northeast. (Web site: http://www2.dnr.cornell.edu/ext/agroforestry/sare/index.htm). Accessed June 2010.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P. & van den Belt, M. 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387:253-260.

Dalgaard T., Halberg, N. & Porter, J. R. 2001. A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agric Ecosyst Environ*, 87:51-65.

deCarbonnel, E. 2009. Catastrophic fall in 2009 global food production. (Available at: http://www.globalresearch.ca/index.php?context=va&aid=12252). Accessed June 2010.

Dixon, J., Gulliver, A., Gibbon, D. & Hall, M. 2001. *Farming systems and poverty: Improving farmers' livelihoods in a changing world.* Food and Agriculture Organization. (Web site: http://www.fao.org/DOCREP/003/Y1860E/y1860e00.htm). Accessed June 2010.

Enete, A.A. & Amusa, T. A. 2010. Determinants of women's contribution to farming decisions in cocoa based agroforestry households of Ekiti State, Nigeria. *Journal of Field Actions: Field Actions Science Reports*, 4, 1.

FAO. 2001. Organically produced foods. Joint FAO/WHO Food Standards Programme, Codex Alimentarius Commission, GL 32-1999, Rev 1-2001. Rome.

FAO. 2006a. *Livestock's long shadow.* Rome. ISBN 978-92-5-105571-7. 377 pp. (Available at: http://www.fao.org/docrep/010/a0701e/a0701e00.HTM).

FAO. 2006b. Conservation agriculture (CA) for sustainable agriculture and rural development (SARD). (Web site: http://www.fao.org/sard/en/sard/754/1458/index.html). Accessed June 2010.

FAO. 2007a. The conservation agriculture for sustainable agriculture and rural development (CA for SARD) Project. (Web site: http://www.fao.org/sard/en/sard/754/2322/2317/index.html). Accessed June 2010.

FAO. 2007b. SARD and…agro-ecology. Sustainable Agriculture and Rural Development (SARD). Policy Brief 11, Rome.

FAO. 2008. Water and cereals in drylands. Rome. 110 pp.

FAO. 2010a. (Web site: http://www.fao.org/agriculture/crops/core-themes/theme/spi/en). Accessed May 2010.

FAO. 2010b. (Web site: http://www.fao.org/nr/land/sustainable-land-management/en/). Accessed June 2010.

FAO. 2010c. (Available at: http://www.fao.org/agriculture/crops/core-themes/theme/spi/en/). Accessed June 2010.

FAO. No date. Conservation Agriculture. (Web site: http://www.fao.org/fileadmin/templates/tc/tce/pdf/Conservation_Agriculture.pdf).

Francis, C., Breland, T.A., Lieblein, G., Moulton, M., Salomonsson, L., Geber, U., Langer, V., Sriskandarajah, N., Porter, J. & Helenius, J. 2006. *Agroecology education and research: an academic platform for organic farming.* Joint Organic Congress, 30 May 2006, Odense, Denmark. (Available at: http://orgprints.org/7275/). Accessed June 2010.

Garrity, D. *et al.* 2010. In press. Evergreen agriculture: A robust approach to sustainable food security in Africa: *Food Security Journal*, Springer Science.

Hine, R. & Pretty, J. 2008. Organic agriculture and food security in Africa. Geneva and New York, United Nations Conference on Trade and Development (UNCTAD) and United Nations Environment Programme (UNEP).

Hobbs, P.R., Sayre, K. & Gupta, R. 2008. The role of conservation agriculture in sustainable agriculture, Philosophical transactions of the Royal Society of London. Series B, *Biological Sciences*, 363:543-555.

International Water Management Institute. 2007. Water for Food, Water for Life: A comprehensive assessment of water management in agriculture. D. Molden (ed), London, Earthscan.

Institut de Recherche pour le Développement. 2008. Agricultures traditionnelles: une diversité inattendue, des préceptes à l'épreuve du temps. *Actualité Scientifique*. Issue no.301, Jun 2008. Précis from E. Mollard and

A. Walter (eds). 2008. Agricultures singulières, Paris, *Editions IRD*. 344pp.

International Union for Conservation of Nature. 2008. *Learning from landscapes*. Special Edition of Arborvitae. Gland, Switzerland IUCN Forest Conservation Programme.

Kinsella, J. 1995. The effects of various tillage systems on soil compaction. pp.15-17. *In Farming for a better environment.* Ankeny, IO, United States, Soil and Water Conservation Society.

Kwa, A. 2001. *Agriculture in developing countries: which way forward?* Focus on the Global South, Trade-Related Agenda Development and Equity, Occasional Papers 4. *South Centre*. (Available at: http://www.focusweb.org/publications/2001/agriculture_which_way_forward.html). Accessed June 2010.

Mayett, Y., Martinez-Carrera, D., Sanchez, M., Macias, A., Mora, S. & Estrada-Torres, A. 2006. Consumption trends of edible mushrooms in developing countries: The case of Mexico. *Journal of International Food & Agribusiness Marketing,* Vol. 18(1/2):151-176

McNeely, J. A. & Scherr, S. J. 2003. *Ecoagriculture: Strategies to feed the world and save wild biodiversity.* Washington, DC, Island Press.

Müller-Lindenlauf, M. / FAO. 2009. *Organic agriculture and carbon sequestration possibilities and constraints for the consideration of organic agriculture within carbon accounting systems.* Rome.

Naerstad, A. 2007. *Africa can feed itself.* Oslo, The Development Fund.

Neely, C., Bunning, S. & Wilkes, A. 2009. *Review of evidence on drylands pastoral systems and climate change: Implications and opportunities for mitigation and adaptation.* Rome, FAO.

North Carolina State University. 2001. (Web site: http://www.ncsu.edu/sustainable/tillage/tillage.html). Accessed June 2010.

Parrott, N. & Marsden, T. 2002. *The real Green Revolution: Organic and agroecological farming in the South.* London, *Greenpeace Environment Trust.*

Pasture Cropping. 2010. (Web site: http://www.pasturecropping.com). Accessed May 2010.

Perfecto, I. & Vandermeer, J. 2010. The agroecological matrix as alternative to the land-sparing/agriculture intensification model. *PNAS*, 107:5786-5791.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D. & Seidel, R. 2005. Environmental, energetic and economic comparisons of organic and conventional farming systems. *Bioscience*, 55:573-582.

Pretty, J. 2009. Can Ecological Agriculture Feed Nine Billion People? *Monthly Review*, Nov 2009. (Available at: http://www.monthlyreview.org/hungerandprofit.php). Accessed June 4, 2010.

Pretty, J., Noble, A. D., Bossio, D., Dixon, J., Hine, R.E., Penning de Vries, F.W.T. & Morison, J.I.L. 2006. Resource-conserving agriculture increases yields in developing counties. Environmental Science & Technology, 40:1114-19

Pretty, J. & Hine, R. 2001. *Reducing food poverty with sustainable agriculture: a summary of new evidence.* United Kingdom, University of Essex Centre for Environment and Society.

Quisumbing, A. R. 1995 *Gender differences in agricultural productivity: a survey of empirical evidence.* Washington, DC, IFPRI. (Web site: http://ideas.repec.org/p/fpr/fcnddp/5.html). Accessed April 2010.

Reardon, T. & Vosti, S.A. 1995. Links between rural poverty and the environment in developing countries: Asset categories and investment poverty. *World Development*, 23:1495-1506.

Savory, A. with J. Butterfield. 1999. *Holistic management: A new framework for decision making.* Washington, DC, Island Press.

Scialabba, N. E-H. & Hattam, C. (eds). 2002. Organic agriculture, environment and food security. Rome, FAO.

Seis, C. 2006. Pasture cropping: Techniques and equipment. *Australian Organic Journal*, Summer.

Spieldoch, A. & Murphy, S. 2009. Agricultural land acquisitions: Implications for food security and poverty alleviation In *Land Grab? The Race for the world's farmland.* Kugelman, M. & S. L. Levenstein (eds). Washington, DC, Woodrow Wilson International Center for Scholars, Asia Program.

Stanhill, G. 1990. The comparative productivity of organic agriculture. *Agric Ecosyst Environ*, 30, pp.1-26.

UNCCD. 2009. United Nations Convention to Combat Desertification. (Web site: www.unccd.int).

United Nations Conference on Trade and Development / United Nations Environment Programme. 2008. Organic Agriculture and Food Security in Africa, UNEP-UNCTAD Capacity-Building Taskforce on Trade, Environment and Development. New York and Geneva.

United Nations Development Programme. 1995. Agroecology: Creating the synergism for a sustainable agriculture. *UNDP Guidebook Series*, New York.

United Nations Environment Programme. 2005. *Agroecology and the search for a truly sustainable agriculture.* Mexico DF, United Nations Environment Programme (UNEP).

Uphoff, N. 2003. Higher yields with fewer external inputs? The system of rice intensification and potential contributions to agricultural sustainability. *Int J Agric Sustain,* 1:38-50.

United States Department of Agriculture. 1997. Forest Farming: An agroforestry practice. *Agroforestry Notes,* Nov 1997.

Van t'Hooft, K. 2009. Livestock: friend or foe? The need to look at production systems in the debate about livestock & climate change. ETC Foundation, *New Agriculturalist*, Jan 2009.

Woodfine, A. 2009. Using sustainable land management practices to adapt to and mitigate climate change in sub-Saharan Africa. *TerrAfrica*, Aug 2009.

WOCAT. 2009. World Overview of Conservation Approaches and Technologies. Soil and Water Conservation Technologies Data Base. (Available at: http://www.fao.org/ag/agl/agll/wocat/wocatqt.asp). Accessed June 2010.

World Resources Institute; Department of Resource Surveys and Remote Sensing, Ministry of Environment and Natural Resources, Kenya; Central Bureau of Statistics, Ministry of Planning and National Development, Kenya; and International Livestock Research Institute. 2007. *Nature's benefits in Kenya, An atlas of ecosystems and human well-being.* Washington, DC and Nairobi, World Resources Institute.