Production Systems for Sustainable Intensification

Integrating Productivity with Ecosystem Services

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At present, the predominant form of agriculture is based on the *interventionist* approach, in which most aspects of the production system are controlled by technological interventions (such as soil tilling, curative pest and weed control with agrochemicals) and the application of synthetic mineral fertilisers for plant nutrition. However, there are now many production systems with a predominantly *ecosystem* approach, underpinned by healthy soils, and characterised as "Conservation Agriculture", that are not only effective in producing food and other raw materials economically, but also more sustainable in terms of environmental impacts. Their further development and spread merit deeper support with the development of suitable policies, funding, research, technologies, knowledge-diffusion, and institutional arrangements.

1 Introduction

Sustainable production systems which use all appropriate best management practices should offer the best possible agricultural outputs from efficient factor productivities that also minimise risks and ensure ecological sustainability and resilience to underpin economic and social sustainability. They can provide the following major benefits to producers (benefits i and ii), at any scale and type of soil-based farming, and to society at large (benefits iii and iv):

i. Higher stable production, productivity, and profitability with lower input and capital costs;
ii. Capacity for climate change adaptation and reduced vulnerability to extreme weather conditions;
iii. Enhanced and ongoing provision of ecosystem functions and services;
iv. Reduced greenhouse gas emissions.

It has become increasingly clear that most crop production systems are both economically and environmentally vulnerable and unsustainable. Agricultural sustainability has become more uncertain in recent years, relating to the sharp rise in the cost of food and energy, climate change, water scarcity, degradation of ecosystem services and biodiversity, and the financial crisis. The expected increase in population and the associated demands for food, water and other agricultural products will bring additional pressures. In recent decades, many influential people and organisations have been highlighting the need for the development of sustainable agricultural systems. In response to this, action has been promoted at all levels, but – as witnessed in the Millennium Ecosystem Assessment (MEA 2005), the World Development Report 2008 (WDR 2008), the IAASTD reports (McIntyre et al. 2008), and the Royal Society (2009) – some agricultural systems are still being promoted which have unacceptably high environmental, economic, and social costs (Kassam et al. 2009). These are representative of the "interventionist approach" in which most aspects of the production system are controlled by human technological interventions.

2 Principles and Concepts of Sustainable Intensification

The balanced cycling of carbon between the atmosphere, plants, and soil is the basis of sustainability. The profitability and sustainability of production systems – managed by both large- and small-scale farmers – derive from efficiency in both the use and conservation of available resources, applied in appropriately-combined crop-soil-water-nutrient-pest-ecosystem management practices. These practices are locally devised and adapted to capture a range of productivity, socioeconomic and environmental co-benefits of agriculture and ecosystem services at the farm, landscape, and provincial or national scale (Pretty 2008; Kassam et al. 2009; Godfray et al. 2010; FAO 2010; Pretty et al. 2011; Foresight 2011; UKNEA 2011).

There are now a growing number of production systems which follow a predominantly *ecosystem approach*. These sustainable systems offer a range of productivity, socio-economic, and environmental benefits to producers and to society at large. They are based on five overall objectives:

a) Simultaneous achievement of increased agricultural productivity and enhanced ecosystem services.
b) Enhanced input-use efficiency, including water, nutrients, pesticides, energy, land, and labour.
c) Judicious use of external inputs derived from fossil fuels (such as mineral fertilisers and pesticides) and preference for alternatives (such as recycled organic matter, biological nitrogen fixation, and integrated pest management).
d) Protection of soil, water, and biodiversity through use of "minimum soil disturbance" and maintaining organic matter cover on the soil surface to protect the soil and enhance soil organic matter and soil biodiversity.
e) Use of managed and natural biodiversity of species to build systems' resilience to abiotic, biotic, and economic stresses, with an underlying emphasis on improving soils' content of organic matter as a substrate essential for the activity of the soil biota.

The farming practices required to implement these objectives will differ according to local conditions and needs, but will have to comprise the following elements:

1. *Minimizing soil disturbance by mechanical tillage* (once brought to good porous condition), and, whenever possible, seeding or planting directly into untilled soil, in order to maintain soil organic matter, soil structure, and overall soil health.
2. *Enhancing and maintaining organic matter cover on the soil surface*, using crops, cover crops, or crop residues. This protects the soil surface, conserves water and nutrients, promotes soil biological activity and contributes to integrated weed and pest management.
3. *Diversification of species* – both annuals and perennials – in associations, sequences, and rotations that can include trees, shrubs, pastures, and crops, all contributing to enhanced crop nutrition and improved system resilience.

These practices are those generally associated with Conservation Agriculture (CA), now widely used in all continents. However, these CA practices need to be strengthened by additional "best management practices":

4. Use of well adapted, high yielding varieties and good quality seeds
5. Enhanced crop nutrition, based on healthy soils
6. Integrated management of pests, diseases, and weeds
7. Efficient water management

Sustainable crop production intensification is the combination of all seven of these improved practices applied in a timely and efficient manner. Such sustainable production systems are knowledge-intensive and relatively complex to learn and implement. They offer farmers many possible combinations of practices to choose from and adapt, according to their local production conditions and constraints (Pretty 2008; Kassam et al. 2009; Godfray et al. 2010; FAO 2010; Meyer 2010; Pretty et al. 2011).

A main criterion for ecologically sustainable production systems is the maintenance of an environment in the root-zone to optimise soil biota, including healthy root functions, to the maximum possible depth. Roots are thus able to function effectively and without restrictions to capture plant nutrients and water as well as interact with a range of soil microorganisms beneficial for soil health and crop performance (Shaxson 2006; Uphoff et al. 2006; Pretty 2008). In such systems with the above attributes there are many similarities to resilient "forest floor" conditions (Shaxson et al. 2008; Kassam et al. 2009). Maintenance or improvement of soil organic matter content and biotic activity, soil structure, and associated porosity, are critical indicators for sustainable production and other ecosystem services.

A key factor for maintaining soil structure and organic matter is to limit mechanical soil disturbance in the process of crop-management. This is because it provokes accelerated oxidation of organic matter and loss of the resulting CO_2 back into the atmosphere. In so doing, it depletes soil organic matter, the energy-rich substrate for the life processes of the soil biota which are essential for developing and maintaining any soil in a healthy and productive condition. The contribution of practices that implement the technical principles – including mulch cover, no-tillage, crop rotations, and legume crops – to important ecosystem services is shown in Table 1. Even where it is not possible to install all desirable practical aspects in the production system at the same time, progressive improvements towards those goals are to be encouraged. Nevertheless, for any agricultural system to be sustainable in the long term, the rate of soil formation – from the surface downwards – must exceed the rate of any degradation due to loss of organic matter (living and/ or non-living), and of soil porosity, evidenced by

Table 1: Agro-ecosystem features relating to the component practices of Conservation Agriculture

SYSTEM COMPONENT ► *RELEVANT FEATURE ▼*	*NO TILLAGE (minimal or no soil disturbance)*	*MULCH COVER (crop residues, cover-crops, green manures)*	*CROP ROTATION (for safety, biodiversity, profit, etc.)*	*LEGUMES (for fixing nitrogen, supplying nutrients, creating biopores)*
Simulate optimum "forest-floor" conditions	√	√		
Reduce evaporative loss of moisture from soil surface	√	√		
Reduce evaporative loss from soil upper soil layers	√	√		
Minimise oxidation of soil organic matter, CO_2 loss	√			
Minimise compactive impacts by intense rainfall, passage of feet, machinery	√	√		
Minimise temperature fluctuations at soil surface	√	√		
Maintain regular supply of organic matter as substrate for soil organisms' activity	√	√	√	√
Increase, maintain nitrogen levels in root-zone	√	√	√	√
Increase CEC of root-zone	√	√	√	√
Maximise rain infiltration, minimise runoff	√	√		
Minimise soil loss in runoff, wind	√	√		√
Permit, maintain natural layering of soil horizons by actions of soil biota	√	√		
Minimise weeds	√	√	√	√
Increase rate of biomass production	√	√	√	√
Speed soil-porosity's recuperation by soil biota	√	√	√	√
Reduce labour input	√	√		
Reduce fuel-energy input	√		√	√
Recycle nutrients	√	√	√	√
Reduce pest-pressure of pathogens			√	
Re-build damaged soil conditions and dynamics	√	√	√	√
Pollination services	√	√	√	√

Source: Adapted from Friedrich et al., 2009 consequent soil erosion. In the majority of agro-ecosystems this is not possible if the soil is mechanically disturbed (Montgomery 2007). For this reason the avoidance of unwarranted mechanical soil disturbance is a starting point for sustainable production. Not tilling the soil is therefore a necessary condition for sustainability, but not a sufficient condition: other complementary techniques are also required.

3 Potential Constraints to Sustainable Production Intensification Systems

Some farming regions present special challenges for introducing sustainable agro-ecological production systems. For example in sub-humid and semi-arid climatic zones it may not be possible to apply the precepts of such systems to an optimum, particularly in the early phases of adoption, because lack of rainfall may limit how much biomass can be grown per unit area. Since in these regions water is normally the limiting factor, the water savings from not tilling generally result in yield increases already in the first years which compensate for the amounts of residue left on the fields which otherwise could have been removed for forage purposes.

In more humid areas, scarcities of particular plant nutrients may prove to be the more significant factors. For example, relief of phosphorous deficiency may enable better crop responses to other inputs. There is evidence that due to the higher soil biological activity in the systems described above long-term availability of phosphorus and other nutrients can be enhanced (Uphoff et al. 2006).

Poorly-drained and/or compacted soils are also generally not optimal for cropping under either high or low soil disturbance. However, if the origin of bad drainage is a soil horizon with low water permeability beyond the reach of soil-loosening equipment, it is only through biological means such as tap roots and soil organisms (e.g. earthworms) that such deep obstacle to water percolation can be eventually broken up, whose actions are facilitated by minimal soil disturbance systems over time. In most circumstances soil compaction needs to be eliminated or reduced where it already exists and future compactions avoided by minimal soil disturbance in any management activity.

Improvement of organic-matter levels and associated biological activity in the soil can have multiple positive effects which may alleviate/eliminate more than one limiting factor at the same time. There have been arguments that no-tillage systems result in increased use of pesticides and herbicides. However, in reality when no-tillage is integrated with the other complementary practices of mulch and bio-diversification, this can lead to decrease in their use, both in absolute amounts, and in terms of quantity of active ingredient applied per tonne of output, compared with tillage agriculture (Baig, Gamache 2009; Lindwall, Sontag 2010). In manual smallholder systems, these systems can also be practiced without herbicides by applying adequate integrated weed management (Owenya et al. 2011).

4 Relevance of Conservation Agriculture for Sustainable Intensification

Sustainable intensification is facilitated with Conservation Agriculture (CA) because biological optimisation of soil conditions is continuous, and repeated “soil-recuperative” breaks (essential in tillage-based systems) are unnecessary.

Being based on no-till and maintenance of soil cover, CA provides a good example of progress in both thought and action, which has now spread into all continents and ecologies (Hobbs 2007; Shaxson et al. 2008; Friedrich et al. 2009; Kassam et al. 2009; Kassam et al. 2010). CA is now adopted on about 117 million ha worldwide – about eight percent of the total cropland. Some 50 percent of this area is located in the developing regions. During the past decade, it has been expanding at an average rate of more than six million ha per year. Highest adoption levels, exceeding 50 percent of the cropland, are found in Canada, Australia, and the southern part of South America. Fast adoption rates are now being seen in Central Asia and China, and early large-scale adoption is taking place across Africa.

Sustainable crop production intensification principles can be readily integrated into other ecosystem-based approaches to generate greater benefits, for example:

System for Rice Intensification (SRI) has proven to be successful as a basis for sustainable intensification in all continents under a wide range of circumstances (see *Uphoff in this volume*). Trained farmers have shown SRI embodies CA Principles to offer higher factor productivities and income, and requires less seeds, water, energy, fertiliser, and labour compared with conventional irrigated or rainfed flooded rice production systems (Kassam et al. 2011).

"Organic" agriculture, when integrating CA, can lead to greater soil health and productivity, increased efficiency of use of organic matter, and reduction in use of energy. Organic CA farming is already practiced in the US, Brazil, and Germany, as well as by subsistence CA farmers in Africa.

Agroforestry systems involve the cultivation of woody perennials and annual crops together in a sustainable manner and, with perennial legumes, are increasingly practised in degraded areas. CA with trees has now become an important option for many farming situations, particularly in the tropics. These CA systems have become the basis for major scaling-up programmes with thousands of farmers in Zambia, Malawi, Niger, and Burkina Faso (Garrity et al. 2010). The incorporation of the indigenous acacia species *Faidherbia albida* into maize-based conservation agriculture in Zambia on a large scale is a noteworthy example (Sims et al. 2009).

Shifting agriculture, (also referred to as "swidden" or "slash and burn"), entails the clearing of land to prepare a cultivation plot and subsequently returning this to re-growth and eventual natural reforestation, during which damaged soil structure and depleted "indigenous" plant nutrients are restored. For sustainable intensification, such systems can be adapted to follow CA principles, changing from slash and burn systems to *slash and mulch* systems with a no-till diversified cropping with intercropping and crop rotations that include legumes and organic matter management to maintain soil fertility and to reduce the need for extra land clearing as in Peru's Colca Valley (Montgomery 2007).

Integrated crop-livestock systems including trees have long been a foundation of agriculture. In recent decades, there have been practical innovations that harness synergies between the production sectors of crops, livestock, and agroforestry. Integration can be on-farm as well as on an area-wide basis. The integration of production sectors can enhance livelihood diversification and efficiency through optimization of production inputs including labour, offer resilience to economic stresses, and reduce risks (Landers 2007; FAO 2010).

5 The Way Forward – Policy, Institutional, Technology and Knowledge Support are Needed

The development of sustainable crop production intensification requires building on the core principles and practices outlined above, and finding ways to support and self-empower producers to implement them all, through participatory approaches and stakeholder engagement. In addition, sustainable crop production intensification must be supported by coherent policies, institutional support, and innovative approaches to overcome any barriers to adoption. Monitoring and evaluating the progress of change in production system practices and their outcomes at the farm and landscape levels is critical.

An enabling environment is the precondition for promoting farmers' interest in undertaking sustainable production intensification and maintenance of ecosystem services. For this, given the necessary understanding, the requirements include effective and integrated development planning and policies backed up by relevant research and advisory/extension systems, and the mobilisation of concerned stakeholders in all relevant sectors.

5.1 Policy and Institutional Support

Principles of sustainable production intensification based on the ecosystem approach form the basis for good and sustainable agricultural land use and management, but require a *significant change in "mind-set"*. This includes the realisation that erosion of soil is generally a *consequence* and symptom of initial land degradation – in the form of induced damage to soil structure in its upper layers – and not its primary cause. This understanding highlights CA as a most significant approach for encouraging and achieving sustainability of productive land uses through making best and careful use of agro-ecosystem processes, rather than trying to usurp their functions by use of less appropriate technologies.

Policy cohesion is critical as all governments already have a number of institutions involved in caring for the development of their natural resources. The fragmented nature of their arrangement (e.g. Agriculture, Forestry, National Parks, Energy, Water), the disconnection to production sectors, and relationships within a government often inhibits their effectiveness. Therefore, it is necessary to ensure that the mandates of all such relevant institutions have a clear awareness of the principles on which sustainable land use is based. A well-organised coordination of policies, programmes, and activities is needed.

Agricultural development policy should have a clear commitment to sustainable intensification. All agricultural development activities dealing with crop production intensification should be assessed for their compatibility with ecosystem functions and their desired services. Any environmental management schemes in agriculture including certification protocols and payments for environmental services that do not promote the emulation of CA principles and practices are unlikely to be economically and environmentally sustainable in the long run.

Appropriate nation-wide programmes and financing, as well as political commitment and strong support policies (by international agencies and national governments), are needed for changes in agricultural production systems to occur. Alongside local adaptation and stakeholder engagement, the introduction of agro-ecosystem approaches require the learning phase of production systems' changes which often implies additional costs for farmers. Pioneers and early adopters face many hurdles before the full benefits of such systems can be reaped. The change-over to no-tillage systems to achieve national impact also requires institutional support to producers and supply-chain service providers.

5.2 Technology and Knowledge Support

Fully developed sustainable production systems are knowledge-intensive and relatively complex systems to learn and implement as they must work with nature and integrate as much as possible of the natural ecosystem processes into the design and management of the production systems. The development of fully-sustainable production systems is a continuing task with many possible permutations for farmers to decide from so as to suit their local production circumstances and constraints. Simple standard technologies are not automatically appropriate. One bottleneck is often the knowledge about the new production system. *Site specific research and advisory/extension* is needed to assist farmers in responding to system changes such as in nutrient requirements, pest, disease and weed problems, etc.

A particular bottleneck for wide adoption is the *availability of suitable equipment* for CA. While on small scale CA can be undertaken without special tools just using a narrow hoe or planting stick, the full benefits of labour saving and work precision can only be achieved using special tools or equipment, such as no-till planters, with associated costs. While appropriate tools exist, their local availability for the farmers in most parts of the world is a real challenge. These bottlenecks can be overcome, for example by facilitating input supply chains, local manufacturing of the equipment, and by offering contractor services or sharing equipment among farmers in a group to reduce the cost for a single farmer.

6 What Needs to Be Done Now?

The core agro-ecological elements of sustainable intensification systems are the practices that implement CA's three principles, plus other best practices dealing with crop management, as well as the integration of pastures, trees, and livestock into the production system and supported by adequate and appropriate farm equipment and power. This concept and the practical implications must be placed at the centre of any effort to intensify production at any farm scale.

The following are the suggested action points for policy-makers in developing and industrialised countries:

- Establish clear and verifiable guidelines, policies, and protocols for agricultural production systems which qualify as sustainable intensi-

fication, including as integral elements Conservation Agriculture, Integrated Pest, Nutrient, Weed and Water management and other desirable practices.
- Institutionalise the new way of farming as officially-endorsed policy in public sector education and advisory services.
- Establish a conducive environment to support this new kind of agriculture, including the provision of suitable technologies, and of inputs through the commercial supply markets.
- Establish incentive mechanisms such as justifiable payments to eco-effective land users for environmental or community services.
- As adoption levels increase and the sustainable intensification becomes an accessible option to every farmer, introduce penalties for polluting or degrading ways of agriculture as additional incentive for late adopters.

Note

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The System of Rice Intensification: An Alternate Civil Society Innovation

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A major strategic decision for meeting global food needs is whether this should be attempted by continuing along the current technological trajectory, or whether divergent paths should be considered. Trends such as shrinking arable land per capita, growing water constraints for agriculture, higher energy and production input costs, and the need to preserve environmental quality give impetus for an agro-ecological approach to sustainable production intensification in which biological processes are utilized to enhance factor and total productivity. The "System of Rice Intensification" (SRI) developed in Madagascar has been demonstrating substantial productivity gains and other benefits through making changes in crop, soil, nutrient, and water management, rather than from introducing new varieties or increasing external production inputs. The scientific controversy over SRI should subside as increasing evidence supporting its claims gets accepted into the published literature.

1 Introduction

The challenge of meeting global food demand in the decades ahead raises a question of strategy: To what extent can this goal be met by doing "more of the same" – by simply continuing along the present technological path and finding better solutions in this direction? Posing this question raises a corollary query: Should we be charting some new avenues to increase food production?

These questions do not presume that there will or can be a wholesale shift to alternative methods of production; this will not in any case be practical or feasible in the short to middle run. However, there are some facts and trends, reviewed below, that suggest we should be considering alternative strategies that diverge from our present technological trajectory.

The conditions under which the food needed to meet population demands in this 21st century