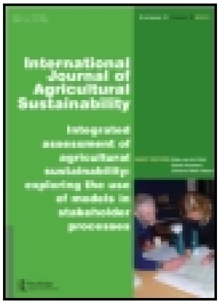

International Journal of Agricultural Sustainability
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tags20

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Parviz Koohafkan [a], Miguel A. Altieri [b] & Eric Holt Gimenez [c]

[a] Land and Water Division, Food and Agriculture Organization (FAO) of the United Nations, Viale delle Terme di Caracalla, 00153, Rome, Italy

[b] College of Natural Resources, University of California, Berkeley, CA, 94720, USA

[c] Institute for Food and Development Policy (Food First), Oakland, CA, 94618, USA

Available online: 17 Nov 2011

To cite this article: Parviz Koohafkan, Miguel A. Altieri & Eric Holt Gimenez (2011): Green Agriculture: foundations for biodiverse, resilient and productive agricultural systems, International Journal of Agricultural Sustainability, DOI:10.1080/14735903.2011.610206

To link to this article: http://dx.doi.org/10.1080/14735903.2011.610206

Green Agriculture: foundations for biodiverse, resilient and productive agricultural systems

Parviz Koohafkan[1], Miguel A. Altieri[2]* and Eric Holt Gimenez[3]

[1] Land and Water Division, Food and Agriculture Organization (FAO) of the United Nations, Viale delle Terme di Caracalla, 00153 Rome, Italy
[2] College of Natural Resources, University of California, Berkeley, CA 94720, USA
[3] Institute for Food and Development Policy (Food First), Oakland, CA 94618, USA

There are many visions on how to achieve a sustainable agriculture that provides enough food and ecosystem services for present and future generations in an era of climate change, increasing costs of energy, social unrest, financial instability and increasing environmental degradation. New agricultural systems that are able to confront the challenges of a rapidly changing world require a minimum of ten attributes that constitute the defining elements of a Green Agriculture. A major challenge is to identify a set of thresholds that any agricultural production strategy must meet, beyond which unsustainable trends caused by the farming technologies would lead to tipping-point phenomena. Only those styles of agriculture that meet the established threshold criteria while advancing rural communities towards food, energy and technological sovereignty would be considered viable forms of Green Agriculture. Considering the diversity of ecological, socio-economic, historical and political contexts in which agricultural systems have developed and are evolving in, it is only wise to define a set of flexible and locally adaptable principles and boundaries of sustainability and resiliency for the agroecosystems of the immediate future.

Keywords: food sovereignty; global agriculture; sustainability; thresholds

Introduction

There are several approaches on how to enhance agricultural yields, ranging from expanding into new land to increasing the yield per hectare via higher input use or genetic modification or increasing the output per unit of inputs such as water, nitrogen or phosphorus (NRC, 2010). Intensification of agriculture via the use of high-yielding crop varieties, fertilization, irrigation and pesticides has contributed substantially to the increases in food production over the last 50 years. The food and agricultural sector has been largely successful in providing for an increasing and wealthier global population (Royal Society, 2009). The rate of growth in total factor productivity in agriculture has exceeded the population growth rate, although in some countries and regions such as Africa, the productivity has been low.

Today, most food and agriculture experts agree that food production will have to increase substantially by 2050 (Godfray *et al*., 2010). Almost 90 per cent of the projected 70 per cent increases in food production are expected to come from intensification, including

*Corresponding author. Email: agroeco3@berkeley.edu

PAGES 1–13, http://dx.doi.org/10.1080/14735903.2011.610206 ISSN: 1473-5903 (print), 1747-762X (online). www.tandfonline.com/tags

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zones where land and water are already scarce. But matters become complicated as the rates of growth of agricultural production have been declining and the competition for scarce land and water resources shows no sign of relaxing. Lately, the growing volatility of food prices has severely impacted on the world's poor, most notably during the food price peaks of 2007–2008 (Holt-Gimenez and Patel, 2009).

The relationship between agricultural intensification, natural resources management and socio-economic development is complex, as production activities impact heavily on natural resources with serious health and environmental implications. When the petroleum dependence and the ecological risks of industrial agriculture are accounted for, serious questions about the social, economic and environmental sustainability of certain agricultural strategies arise (IAASTD, 2009).

Unless the footprints of agriculture are carefully reduced through improved agroecological management, both agricultural systems and remaining natural ecosystems will suffer further degradation, thus increasing the proportion of the world's species threatened with extinction and further limiting the ecosystem services provided by agriculture for humankind (Perfecto *et al.*, 2009). An additional complication is that most modern monoculture systems are particularly vulnerable to climate change and little has been done to enhance their adaptability to changing patterns of precipitation, temperature and extreme weather events (Rosenzweig and Hillel, 2008). This realization has led many experts to suggest that the use of ecologically based management strategies may increase the productivity, sustainability and resilience of agricultural production while reducing undesirable impacts (Altieri, 2002; de Schutter, 2010).

Therefore, a key challenge for the future in the management of agroecosystems lies in increasing the efficiency of resource use in order to ensure increased production and conservation of biodiversity and scarce natural resources, while building in resilience in agroecosystems in the face of increasing climate-related hazards, biotic stresses and economic shocks (Tilman *et al.*, 2002, Pretty *et al.*, 2011).

The requirements of a sustainable agriculture

In his report to the UN Human Rights Council, the UN Special Rapporteur on the right to food stated that in order to take effective measures towards the realization of the right to food, food systems must ensure the availability of food for everyone, warning, however, that increasing food production to meet future needs, while necessary, is not sufficient. The report stressed the fact that agriculture must develop in ways that increase the incomes of smallholders and of poor consumers as hunger is caused not by low food stocks but by poverty. It also emphasized that agriculture must not compromise its ability to satisfy future needs by undermining biodiversity and the natural resource base. The report highlights the potential of agroecology as the best approach to move towards the realization of the right to adequate food in its different dimensions: availability, accessibility, adequacy, sustainability and participation (de Schutter, 2010).

Although there is no consensus on a particular definition of sustainable agriculture, promoting a new agricultural production paradigm in order to ensure the production of abundant, healthy and affordable food for an increasing human population is an urgent and unavoidable task. This challenge will have to be met using environmentally friendly and socially equitable technologies and methods, in a world with a shrinking arable land base (which is also being diverted to produce biofuels), with less and more expensive petroleum, increasingly limited supplies of water and nitrogen and within a scenario of a rapidly changing climate, social unrest and economic uncertainty (IAASTD, 2009). The only agricultural system that will be able to confront future challenges is one that will exhibit high levels of diversity, productivity and efficiency (top left quadrant in Figure 1, Funes-Monzote, 2009). To transform agricultural production so that it not only produces abundant food but also becomes a major contributor to global biodiversity conservation and a continuing source of redistributive ecosystem and socio-economic services is unquestionably a key endeavour for both scientists and farmers in the second decade of the 21st century (Godfray *et al.*, 2010).

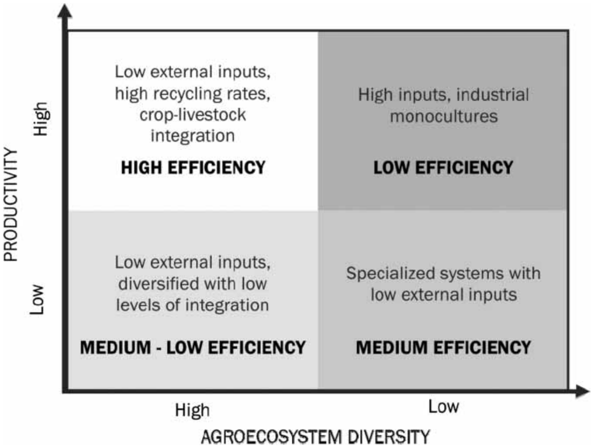

Figure 1 | Features of green agroecosystems of the future: productivity, diversity, integration and efficiency
Source: Funes-Monzote (2009).

Standards for sustainable agriculture

Several sustainable agriculture standard-setting initiatives are under way aiming at establishing a comprehensive, continuous improvement framework with a common set of economic, environmental and social metrics to determine whether an agricultural system is being managed in a sustainable manner (e.g. the sustainable agriculture standard of the Leonardo Academy (2007) and the Global Bioenergy Partnership, 2010). In addition, several agricultural enterprises interested in implementing a sustainability programme are engaged in developing a self-assessment protocol of their particular agricultural operations. The main idea is for the enterprise promoting an agricultural development or business model to find ways to implement the sustainability plan in order to assess its goals and use methods that improve its performance in the environmental and economic spheres. Several companies have developed their own sustainable agriculture code and ask their suppliers, and the farmers who supply them, to adopt sustainable practices on their farms. For example, Unilever adopted a series of agricultural sustainability principles (Pretty *et al*., 2008a) and expects all their suppliers of agricultural raw materials to commit to minimum standards of performance and to continuously improve performance over time to reach sustainability targets. During an analysis of this initiative, researchers selected 10 sustainability indicators for various crops (peas, spinach, tomatoes, tea and oil palm) in 11 countries to assess progress towards the sustainable supply of these crops (Pretty *et al*., 2008b). Apparently, these assessments have been important for Unilever in developing a more mature approach to measuring and monitoring agricultural sustainability. However, due to methodological and institutional constraints, multi-indicator, multi-year monitoring programmes as originally envisaged are unlikely to be applicable to whole product supply chains in the short term.

The idea behind establishing a set of agronomic, ecological, social, economic and environmental standards is that if contracted producers follow such standards they should be able to promote a more efficient agriculture, biodiversity conservation and benefit their communities. The use of the standards and the auditing of such standards should foster best management practices that support sustainability and resilience. Compliance is evaluated by audits conducted by authorized inspection and/or certification bodies that measure the degree of the farm's conformity to the environmental and social norms indicated in the standard's criteria. As a tool the method is useful for companies and associated farmers interested in mitigating environmental and social risks caused by their agricultural activities through a process that motivates continual improvement, as well as provide a measure of each farm's social and environmental performance and best management practices. For example, the Rainforest Alliance (2007) developed a series of standards that cover the environmental, social, labour and agronomic management of farms. The Rainforest Alliance certification is built on the three pillars of sustainability: environmental protection, social equity and economic viability. Among the trends expected in tropical farms that follow the standards are less soil erosion, pollution and waste, enhanced habitat for wildlife, reduced threats to human health and improved conditions for farm workers.

Recently, Conservation International and the Bill and Melinda Gates Foundation convened a workshop to create a network for the global monitoring of agriculture, ecosystem services and livelihoods. The goal of the network will be to provide a system for integrated measurement and analysis of agriculture's human well-being and environmental outcomes to ensure that agricultural development is sustainable (Conservation International, 2011). They proposed a group of three types of metric and synthetic indicators to be used during the agricultural intensification process:

1. a set of indicators to identify areas suitable either for intensification or for ecosystem services;
2. indicators to assess the performance of the intensification process;
3. situational awareness indicators to capture the different dimensions of impact of intensification.

An apparent drawback of this proposal is that it identifies intensification (increase the production per area via the efficient use of inputs) as the only agricultural path for agricultural production, disregarding the diversity of other agroecological approaches that, instead of intensification, emphasize diversification, synergies and recycling. The methodology also creates a dichotomy between areas for agriculture and areas for nature, ignoring the fact that there are forms of agriculture (notably smallholder diversified farms) that simultaneously produce food and conserve biodiversity and associated ecosystem services (Perfecto *et al*., 2009).

While such principles and standards are of great importance for assessing the sustainability of agricultural operations, groups engaged in such processes have encountered great difficulty in arriving at agreement on criteria, let alone standards; therefore, a number of shortcomings persist and the application of standards remains rather limited. Some people believe that the imposition of general and rigid standards that may not fit within the specificities of each agricultural region can actually inhibit the diversity of agricultural production approaches and be counterproductive to the evolution of sustainable agriculture. Others argue that the science underpinning such an audit is still not in place. Another problem with many certification schemes is that they judge the farmer rather than the technologies promoted and in most cases it leaves the costs of remediation and conversion to the farmers to meet the certification standards while the enterprises usually continue paying the same prices for products. Many farmers linked to local and regional markets, constrained by standards tailored for export agriculture, have opted for other types of certification programmes, such as the participatory certification of the Rede Ecovida in southern Brazil (Dos Santos and Mayer, 2007). Ecovida consists of a space of articulation between organized family farmers, supportive NGOs and consumers whose objective is to promote agroecological alternatives and develop solidarious markets that tighten the circle between local producers and consumers, ensuring local food security and that the generated wealth remains in the community (Van der Ploeg, 2009).

Basic attributes and goals of a 'Green Agriculture'

There are many competing visions on how to achieve new models of a biodiverse, resilient, productive and resource-efficient agriculture that humanity desperately needs in the immediate future. Conservation (no or minimum tillage) agriculture, sustainable intensification production, transgenic crops, organic agriculture and agroecological systems are some of the proposed approaches, each claiming to serve as the durable foundation for a sustainable food production strategy. Although the goals of all approaches may be similar, technologies-proposed (high- versus low-input) methodologies (farmer led versus market driven) and scales (large-scale monocultures versus biodiverse small farms) are quite different and often antagonistic. With more than a billion hungry people on the planet and future climate and economic disruptions immanent, there is an urgent need for the entire development community to work together to design and scale up truly sustainable agricultural systems.

A starting point is to agree on the basic attributes that a sustainable production system should exhibit. Criteria derived from the extensive literature on agroecology and sustainable agriculture suggest a series of attributes (Table 1) that any agricultural system should exhibit in order to be considered

Table 1 | **Basic attributes of sustainable agricultural systems**

1.	Use of local and improved crop varieties and livestock breeds so as to enhance genetic diversity and enhance adaptation to changing biotic and environmental conditions
2.	Avoid the unnecessary use of agrochemical and other technologies that adversely impact on the environment and on human health (e.g. heavy machineries, transgenic crops, etc.)
3.	Efficient use of resources (nutrients, water, energy, etc.), reduced use of non-renewable energy and reduced farmer dependence on external inputs
4.	Harness agroecological principals and processes such as nutrient cycling, biological nitrogen fixation, allelopathy, biological control via promotion of diversified farming systems and harnessing functional biodiversity
5.	Making productive use of human capital in the form of traditional and modern scientific knowledge and skills to innovate and the use of social capital through recognition of cultural identity, participatory methods and farmer networks to enhance solidarity and exchange of innovations and technologies to resolve problems
6.	Reduce the ecological footprint of production, distribution and consumption practices, thereby minimizing GHG emissions and soil and water pollution
7.	Promoting practices that enhance clean water availability, carbon sequestration, conservation of biodiversity, soil and water conservation, etc.
8.	Enhanced adaptive capacity based on the premise that the key to coping with rapid and unforeseeable change is to strengthen the ability to adequately respond to change to sustain a balance between long-term adaptability and short-term efficiency
9.	Strengthen adaptive capacity and resilience of the farming system by maintaining agroecosystem diversity, which not only allows various responses to change, but also ensures key functions on the farm
10.	Recognition and dynamic conservation of agricultural heritage systems that allows social cohesion and a sense of pride and promote a sense of belonging and reduce migration

sustainable (Gliessman, 1998; Altieri, 2002; UK Food Group, 2010). Most researchers agree that a basic attribute is the maintenance of agroecosystem diversity and the ecological services derived from beneficial ecological interactions among crops, animals and soils. Increasingly, research suggests that the level of internal regulation of function in agroecosystems is largely dependent on the level of plant and animal biodiversity present in the system and its surrounding environment (Altieri and Nicholls, 2004). Biodiversity performs a variety of ecological services beyond the production of food, including recycling of nutrients, regulation of microclimate and local hydrological processes, suppression of undesirable organisms, detoxification of noxious chemicals, etc. (Figure 2). Because biodiversity-mediated renewal processes and ecological services are largely biological, their persistence depends on the maintenance of biological integrity and diversity in agroecosystems. Traditional farmers as well as a generation of agroecologists offer a wide array of management options and designs that enhance functional biodiversity in crop fields (Uphoff, 2002; Altieri and Koohafkan, 2008; Toledo and Barrera-Bassals, 2009).

Another way of exploring the potential sustainability of particular agricultural interventions in addressing pressing concerns is to establish a set of questions (Table 2) that examine whether or not current management practices are contributing to sustainable livelihoods by improving natural, human, social, physical and financial capital. In this regard, many organizations (notably the International Fund for Agricultural Development and UK's Overseas Development Institute) have promoted the sustainable livelihoods approach. This tool provides an analytical framework that promotes systematic analysis of the underlying processes and causes of poverty, food insecurity and environmental degradation. Although it is not the only such framework, its advantages are that it focuses attention on people's own definitions of poverty, food security, etc. and takes into account a wide range of factors that cause or contribute to community problems. These are shown schematically in a framework that identifies the state of the capitals, the threats and the livelihood outcomes, enabling multiple stakeholder perspectives to be taken into

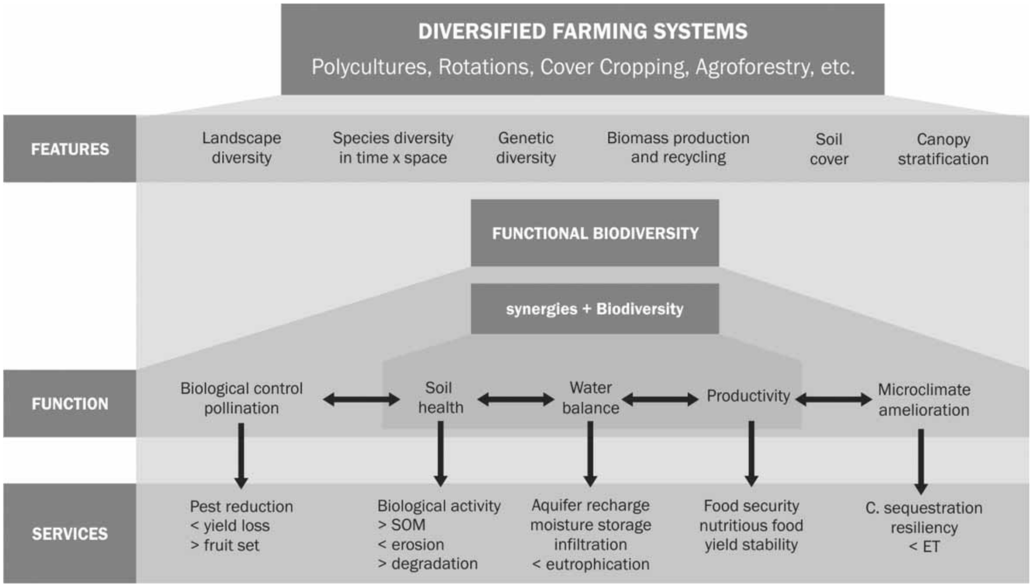

Figure 2 | The ecological role of biodiversity in agroecosystem function and the provision of ecosystem services by diversified farming systems

account in the identification of practical priorities for action to confront the threats and enhance the capitals (Scoones, 2008).

Defining indicators to assess the sustainability of agricultural systems

Agricultural systems – even the most traditional ones – are not static systems; in fact they are constantly changing over time. The major forces that shape current agricultural changes are: population increase and dynamics, global market forces, investment in agriculture and rural sector, important advances in science and technology, climatic change and variability, consumer demands, agricultural subsidies and the pressures from social movements demanding food sovereignty, land reform and poverty reduction. Only food and agricultural policies and practices that are capable of responding adequately to these forces have the possibility of being sustainable in a rapidly changing world.

The design of agroecosystems that exhibit many of the attributes of sustainability (see Table 1) has become a leading objective of scientific research and policy agendas, while their performance assessment remains an important challenge. Many authors have developed methods to evaluate the ecological, economic and social sustainability of particular forms of agriculture at the farm level, estimating the productivity, stability, resilience and adaptability of particular production systems (Hansen and Jones, 1996; Van der Werf and Petit, 2002).

How does a given strategy impact on the overall sustainability of the natural resource management system? What is the appropriate approach to explore the economic, environmental and social dimensions of farming systems? How can the sustainability of an agroecosystem be evaluated? These are unavoidable questions faced by scientists and development practitioners dealing with complex agroecosystems in a rapidly changing world.

At the farm level a major task is to identify indicators that signal performance or specific management problems or identify undesirable environmental changes and what action to take. The focus is on changing practices at the farm scale in a way likely to improve overall farm health (Rigby *et al*., 2001). There is much argument on whether to use location-specific or universal indicators. Some argue that the important indicators of sustainability are location specific and vary

Table 2 | **A set of guiding questions to assess if proposed agricultural systems are contributing to sustainable livelihoods**

1.	Are they reducing poverty?
2.	Are they based on rights and social equity?
3.	Do they reduce social exclusion, particularly for women, minorities and indigenous people?
4.	Do they protect access and rights to land, water and other natural resources?
5.	Do they favour the redistribution (rather than the concentration) of productive resources?
6.	Do they substantially increase food production and contribute to household food security and improved nutrition?
7.	Do they enhance families' water access and availability?
8.	Do they regenerate and conserve soil, and increase (maintain) soil fertility?
9.	Do they reduce soil loss/degradation and enhance soil regeneration and conservation?
10.	Do practices maintain or enhance organic matter and the biological life and biodiversity of the soil?
11.	Do they prevent pest and disease outbreaks?
12.	Do they conserve and encourage agrobiodiversity?
13.	Do they reduce greenhouse gas emissions?
14.	Do they increase income opportunities and employment?
15.	Do they reduce variation in agricultural production under climatic stress conditions?
16.	Do they enhance farm diversification and resilience?
17.	Do they reduce investment costs and farmers dependence on external inputs?
18.	Do they increase the degree and effectiveness of farmer organizations?
19.	Do they increase human capital formation?
20.	Do they contribute to local/regional food sovereignty?

between ecoregions. For example, on hillsides, soil erosion has a major impact on sustainability, but in the flat lowlands, this is insignificant and may not be a useful indicator; rather soil organic matter content may be more relevant. Although usually each indicator deals with one aspect of sustainability, a complete assessment of a farming system should include several indicator values, but instead of being presented separately, they are integrated to provide a more holistic evaluation of socio-economic, agronomic and environmental dimensions (Castoldi and Bechini, 2010).

A strong current of opinion believes that the definition and consequently the procedure for measuring sustainable agriculture is the same regardless of the diversity of situations that prevails on different farms. Under this principle, sustainability is defined by a set of requirements that must be met by any farm regardless of the wide differences in the prevailing situation (Harrington, 1992). The procedure of using a common set of indicators offers a protocol for measuring sustainability at the farm level by: defining the requirements for sustainability and then selecting a common set of indicators to assess whether the requirements are met. According to most methods, a farming system is considered sustainable if it conserves the natural resource base and continues to satisfy the needs of the farmer in the long term. Any system that fails to satisfy these two requirements is bound to degrade significantly over the short term and is therefore considered to be not sustainable.

The Indicator-based Framework for Evaluation of Natural Resource Management Systems (MESMIS) proposes an integrated interdisciplinary approach to assess sustainability of farming systems (Lopez-Ridaura *et al.*, 2002). The framework is applicable within the following parameters:

1. Sustainability of natural resource management systems is defined by seven general attributes: productivity, stability, reliability, resilience, adaptability, equity and self-reliance.
2. The assessment is only valid for a management system in a given geographical location, spatial scale (e.g. parcel, production unit, community, etc.) and determined in a time period.
3. It is a participatory process requiring an interdisciplinary evaluation team. The evaluation team usually includes outsiders and local participants.
4. Sustainability is not measured *per se*, but is measured through the comparison of two or more

systems. The comparison is made either cross-sectionally (e.g. comparing an alternative and a reference system at the same time) or longitudinally (e.g. by analysing the evolution of a system over time).

Using MESMIS, Lopez-Ridaura *et al*. (2002) defined indicators such as independence from external inputs, grain yield, system adoptability, food self-sufficiency, diversity of species, etc. As shown in Figure 3, an AMOEBA-type diagram is used to show, in qualitative terms, how far the objective has been reached for each indicator by giving the percentage of the actual value with respect to the ideal value (reference value). This enables a simple yet comprehensive comparison of the advantages and limitations of the two systems being evaluated and compared, suggesting weak points that may need improvement.

Indicators can also be grouped according to their relevance to the state of the social, economic and natural capital of each farming system being evaluated. The asymmetry of the AMOEBA indicates the extent to which each farming system lacks sustainability or in which aspects each capital is weak. An analysis of the weak points can lead to suggestions of the kinds of interventions necessary to improve the performance of the system. By comparing AMOEBAS from several farming systems, lessons from one location may be transferred to another. Also reconstructing the AMOEBAS in each farm, every year after agroecological interventions, can indicate whether progress is being made towards or away from sustainability.

Defining thresholds of performance for a Green Agriculture

Most agricultural scientists and developers agree on the need to design an agriculture that respects the

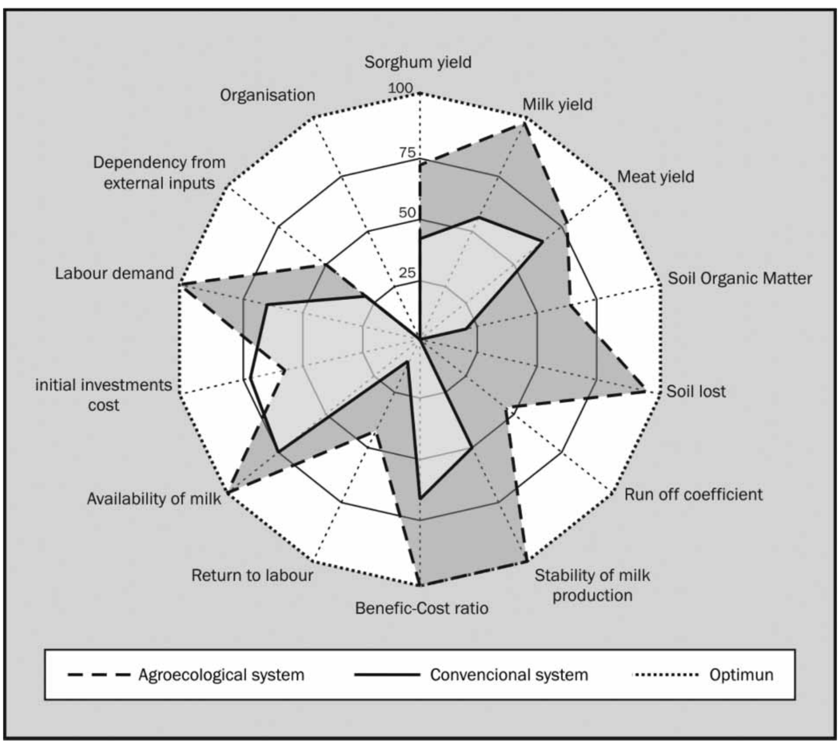

Figure 3 | An AMOEBA diagram with indicators comparing two agrosilvopastoral systems (agroecological versus conventional) in Mexico. Indicators are in original units and as percentages of locally derived optimums
Source: Lopez-Ridaura *et al*. (2002).

limits of the local/regional natural resources, including the capacity to provide ecological services (Pretty *et al*., 2011). For this reason, it is important to identify such limits before reaching the tipping points (thresholds) that lead to potential long-term or irreversible consequences. In each region, a desirable range of values for a set of selected indicators should be defined and maintained within such ranges for normal functioning of local agroecosystems. Within this critical range, the agroecosystem should perform its multiple functions. Given the complexities of arriving at critical parameter values and the fact that indicators interact with each other (the value of one is affected by one or more selected parameters), perhaps the best that can be done is to develop a set of guidelines that can help set limits for defined crop/environment situations.

As discussed above, although numerous indicators of sustainability exist, very few of them suggest and monitor threshold phenomena. Thresholds can be defined as non-linear transitions in the functioning of human-managed systems, such as crop disease epidemics occurring in large areas caused by anthropogenic interventions (i.e. planting large-scale monocultures of a narrow genetic base; Carpenter *et al*., 2001). Some agroecosystem processes are not associated with known thresholds at the field or landscape level, but may, through continuous decline of key ecological functions (such as loss of beneficial biodiversity), cause functional collapses, generating feedbacks that trigger or increase the likelihood of reaching thresholds in other processes such as loss of pest regulation or biologically mediated soil fertility.

Borrowing from the concept of planetary boundaries developed by Rockström *et al*. (2009), it may be possible to establish values of several control variables set at a 'safe' distance from a dangerous level. Determining a safe distance involves normative judgements of how scientists and farmers choose to deal with risk and uncertainty in agriculture. Certain boundaries have already been transgressed in agriculture (i.e. pesticide resistance by more than 500 arthropod species, rapid decline of crop pollinators, etc.). A problem is that boundaries are interdependent, because transgressing one may either shift the position of other boundaries or cause them to be transgressed. The social and ecological impacts of transgressing boundaries will be a function of the resilience of the affected rural and urban societies. Walker and Metes (2004) describe an evolving database that focuses on ecological and linked social systems, in particular those that exhibit thresholds in relation to the use of ecosystems in natural resource management. In characterizing the examples, emphasis is placed on describing the threshold: the variables along which the threshold occurs, the variables that change as a consequence of the shift and the factors that have driven the change.

One of the few methodologies available that specify threshold levels for selected indicators is that described by Gomez *et al*. (1996). Using threshold levels (minimum value of an indicator above which a trend towards sustainability starts), the authors used yields, profit and stability (frequency of disaster) as farmer satisfaction indicators, while soil depth, water holding capacity, nutrient balance, organic matter content, ground cover and biological diversity were used as indicators of resource conservation. According to these researchers, an indicator is said to be at a sustainable level if it exceeds a designated trigger or threshold level; thresholds are tentatively set, based on the average local conditions. Table 3 provides values derived from an evaluation of 10 farms in Cebu, Philippines. The individual farm values for an indicator are compared with the threshold, where meeting an indicator's threshold receives a score of one. Only farms that exhibit average rating of more than 1.0 for farmer satisfaction and resource conservation are considered to be sustainable. Thus, in Farm 5, frequency of crop failure is below the threshold but yield and income are high enough to compensate for this deficiency; however, this ability to compensate is allowable only among indicators of the same index (i.e. within farmer satisfaction) but not across. Thus, excess in yield or income cannot compensate for deficiencies in soil depth and organic matter.

A litmus test for a Green Agriculture

As explained above, the idea is to identify a set of thresholds that any agricultural production strategy must meet beyond which unsustainable trends

Table 3 | **Threshold sustainability indicators for 10 farms in Cebu, Philippines**

Farm no.	Satisfaction farmer				Resource conservation				Sustainability index
	Yield	Profit	Crop failure	Index	Depth	OM	Ground cover	Index	
1	1.18	1.40	1.33	1.30	1.69	1.65	1.66	1.66	1.48
2	0.89	0.90	1.00	0.93	1.15	0.49	0.93	0.85	NS
3	0.89	1.08	1.00	0.99	1.25	0.68	1.13	1.02	NS
4	1.26	1.37	0.66	1.10	0.54	0.57	0.93	0.68	NS
5	1.09	1.13	0.80	1.01	1.24	1.18	1.07	1.16	1.08
6	1.01	1.26	0.80	1.02	1.01	0.75	0.93	0.89	NS
7	0.55	0.21	1.00	0.59	0.68	1.51	0.47	0.88	NS
8	0.32	0.16	1.33	0.60	0.39	0.77	0.00	0.38	NS
9	0.61	0.64	1.00	0.75	1.44	1.64	0.00	1.02	NS
10	0.51	0.16	1.33	0.67	0.61	0.77	0.07	0.48	NS

An average rating of more than 1.0 for farmer satisfaction and resource conservation is required for a farm to be sustainable (Gomez *et al*., 1996).

caused by the farming systems and associated technologies would lead to tipping-point phenomena. For example, it may be argued that transgenic crops can enhance productivity and reduce agrochemical loads. But can it do so by emitting less greenhouse gases (GHGs), without eroding soils or reducing genetic diversity, etc. under allowed threshold values? Others may argue that while organic farming may conserve biodiversity and natural resources and tends to be carbon neutral, it may not yield enough to produce an abundant food supply. Estimates of the economic, social and ecological consequences of transgressing a threshold would suggest that the agricultural strategy should not be deployed and would force the farmers, organization or enterprise promoting the strategy to refine the production system or technology so that when deployed its impacts remain within the acceptable threshold bounds. A threshold-based assessment approach can (a) provide early warnings of impending damages or losses in the healthfulness of the socio-ecological system before a threshold is surpassed, (b) monitor actual system changes once the technology is deployed and (c) suggest alternatives on how the launched technologies can remain within the established thresholds.

As depicted in Figure 4, in order for an agricultural strategy to fit within the Green Agriculture criteria, it must contain the basic requirements of a viable and durable agricultural system capable of confronting the challenges of the 21st century while carrying out its productive goals within certain limits in terms of environmental impact, land degradation levels, input and energy use, GHG emissions, etc. Defined threshold indicators are site or region specific; thus their values will change according to prevailing environmental and socio-economic conditions. In the same region, threshold value ranges may be the same for an intensive large-scale system and a low-input small-scale system as yields will be measured per unit of GHG emitted, per unit of energy or water used, per unit of N leached, etc. Systems that surpass the threshold levels will not be considered sustainable and therefore will require modifications.

Much of the uncertainty in quantifying thresholds is due to a lack of scientific knowledge about the nature of the biophysical thresholds themselves, the intrinsic uncertainty of how complex systems behave, the ways in which other biophysical processes such as feedback mechanisms interact with the primary control variable and uncertainty regarding the allowed time of overshoot of a critical control variable in the system

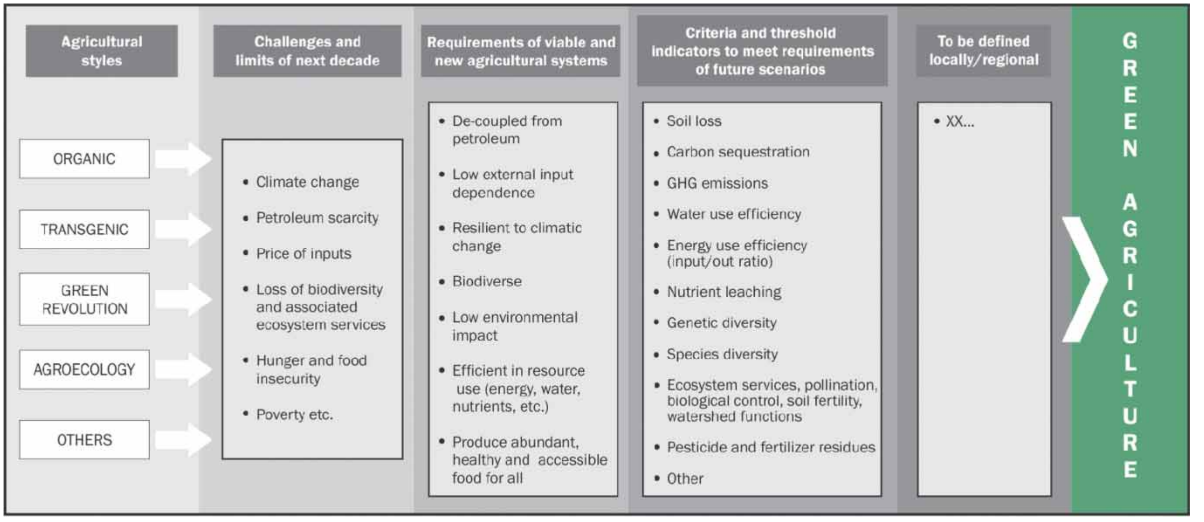

Figure 4 | The basic requirements of a viable and durable agricultural system capable of confronting the challenges of the 21st century while carrying out its productive goals within certain thresholds established locally or regionally

before a threshold is crossed (Rockström *et al*., 2009). This generates a zone of uncertainty around each proposed threshold. Undoubtedly, proposed thresholds may at first be rough estimates only, surrounded by large uncertainties and knowledge gaps. Filling in these gaps will require major advancements in agroecology and resilience science applied at the local level to capture the specificities of each region.

Thresholds can also be established by examining whether the proposed technologies or agricultural

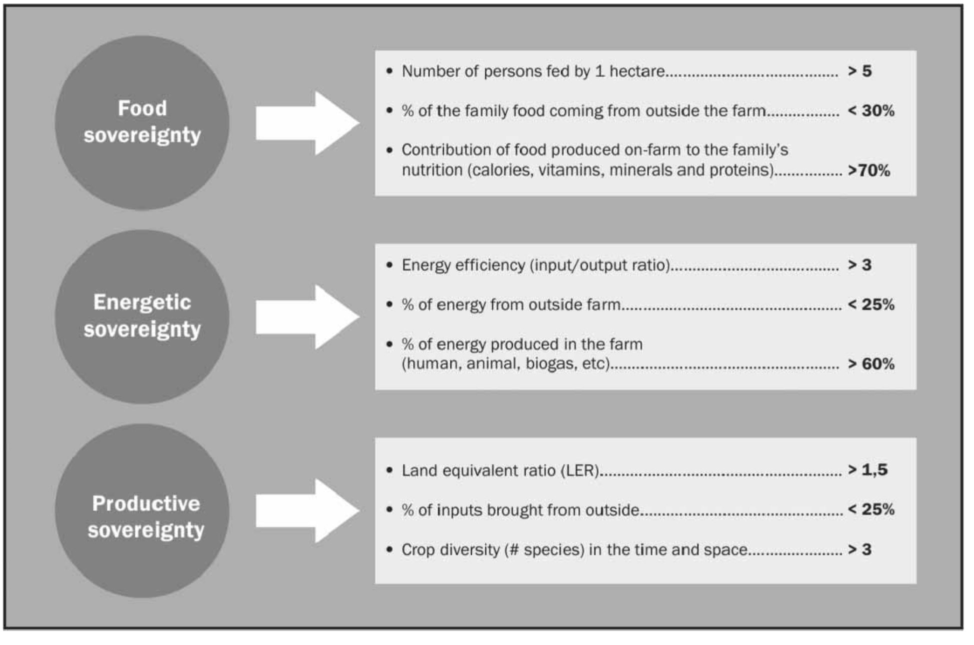

Figure 5 | Hypothetical threshold values established for an agricultural community for each type of sovereignty systems reach the basic requirements of food, energy and technological sovereignty. Food sovereignty is the right of everyone to have access to safe, nutritious and culturally appropriate food in sufficient quantity and quality to sustain a healthy life with full human *dignity*. Similarly, energy sovereignty is the right for all people to have access to sufficient energy within ecological limits from appropriate sustainable sources for a dignified life. Technological sovereignty refers to the capacity to achieve the other two forms of sovereignty by nurturing the environmental services derived from existing agrobiodiversity and using locally available resources. A household, community or region could be called sovereign if it meets the threshold levels established in a participatory manner for each type of sovereignty, as illustrated by a hypothetical example depicted in Figure 5. Arriving at agreed values among all stakeholders may prove difficult, and values will vary from one community to another. Nevertheless, the method provides a framework for rural communities to determine the minimum acceptable values for food production, biodiversity conservation, energy efficiency, etc., allowing them to assess whether or not they are advancing towards a basic state of food, energy and technological sovereignty.

There is an urgent need to assess how well society is doing at increasing agricultural production while simultaneously conserving biodiversity and associated ecosystem services in an era of climate change, energy costs and financial instability. There are a number of analytical tools proposed for estimating agricultural, environmental, economic and social indicators as well as thresholds. The challenge is to arrive at a consensus on the set of metrics and the institutional mechanisms to be used in the auditing of various production systems and/or technologies being proposed or deployed by major international and national organizations (private or public). Whatever the agreed upon mechanisms, only those styles of agriculture that meet the established threshold criteria and that advance communities towards food, energy and technological sovereignty would then be considered as a Green Agriculture system. Such systems then should be scaled up given their capacity for producing enough food while providing ecosystem services within the climatic, energetic, ecological and economic limitations of the next two decades or so.

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