APPROACHES TO ASSESSING SUSTAINABLE AGRICULTURE

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This paper brings together several case studies in which different methodological approaches and techniques mobilizing single or composite indicators were applied to assess agricultural sustainability at four hierarchical levels, including the land management system, the cropping system, the farming system, and the agricultural sector system. The first case study (Iran) focuses on the land management system at the level of individual soil units, using statistical quality control charting to assess the soil fertility status and its effect on agricultural sustainability. Statistical limits are adequate to monitor the behavior of a data population over time, but must be replaced by acceptance/sufficiency standards for sustainability assessment. A relevant limitation of control charting is that large data sets are needed to allow for random sample data selection from the whole population and check for normal distribution of the data. The second case (Kenya) concentrates on the cropping system at parcel level, using yield gap analysis to evaluate sustainable crop productivity. Although yield gap analysis does not indicate by itself what yield level is sustainable, it points at levels of crop productivity higher than farmers' yields, which could be achievable with additional inputs and improved management practices. If the farmer can raise the yield to a higher level, his/her farming activity will become more profitable and therefore more sustainable. The third study (Iran) refers to the farming system at the production unit level, using the energy balance analysis to compare the sustainability of traditional and modern agricultural systems. Energy balance analysis has the advantage of expressing all input and output parameters in the same unit. The approach allows us to establish input/output ratios and compare different farming systems in quantitative terms for assessing their sustainability, but it must be combined with complementary techniques to cover the many facets of the sustainability concept. The last case study (Venezuela) addresses the agricultural sector as a whole, using an aggregated index to monitor the sustainability of the farming activity at regional/national level. Component indicators must be chosen according to data availability, data sensitivity to temporal changes and the capacity of the data to describe quantitatively the behavior of the agricultural activity. The index needs refinement by integrating additional indicators and by allocating differential weights to the indicators to properly reflect their relevance and dynamics. Much effort is still needed to integrate the methodological approaches in one coherent framework allowing to navigate through the hierarchical levels of the agricultural macro-system and to take into account the many requirements involved in a holistic model of sustainability.

Keywords: Sustainable Agriculture, Land Management System, Cropping System, Farming System.

INTRODUCTION

Sustainable agriculture implies long-term maintenance of natural systems, optimal production with minimum input, adequate income per farming unit, fulfillment of basic food needs, and provision for the demands and necessities of rural families and communities (Brown *et al.* 1987; Liverman et al. 1988; Lynam, Herdt 1989). All definitions of sustainable agriculture promote environmental, economic and social harmony in an effort to attain the meaning of sustainability. Sustainability being a concept, it cannot be measured directly. Appropriate indicators must be selected to determine level and duration of sustainability (Zinck, Farshad 1995; Bell, Morse 1999). An indicator of sustainability is a variable that allows us to describe and monitor processes, states and tendencies of the agricultural production systems at various hierarchical levels, considering agriculture as a hierarchy of systems as proposed by Fresco (1986).

This paper brings together several case studies in which different methodological approaches and techniques mobilizing single or composite indicators were applied to assess agricultural sustainability at four hierarchical levels, including the land management system, the cropping system, the farming system, and the agricultural sector system (Table 1). The first case study (Iran) focuses on the land management system at the level of individual soil units, using statistical quality control charting to assess the soil fertility status and its effect on agricultural sustainability. The second case (Kenya) concentrates on the cropping system at parcel level, using yield gap analysis to evaluate sustainable crop productivity. The third study (Iran) refers to the farming system at the production unit level, using the energy balance analysis to compare the sustainability of traditional and modern agricultural systems. The last case study (Venezuela) addresses the agricultural sector as a whole, using an aggregated index to monitor the sustainability of the farming activity at regional/national level. In each case, a methodological approach adapted to the hierarchical level under study is implemented. Its performance in assessing sustainability is tested and limitations are highlighted.

THE LAND MANAGEMENT SYSTEM: QUALITY CONTROL CHARTING

Approach

Farmers in traditional as well as in modern agricultural systems usually adapt their management practices to the properties of each soil unit. Under prolonged and/or intensive use, these properties suffer modifications and often deterioration, causing changes in soil quality. Their status at any given time, compared to reference values reflecting optimum suitability for specific crops, and their evolution over time provide indication on the sustainability of a given land use type in a soil unit under specific management practices. Statistical methods, including regression and variance analysis, have been used to model soil property variations in space and time and to assess the effect of soil quality changes, caused by mismanagement, on agricultural sustainability. Larson and Pierce (1994) suggested that statistical quality control charts (SQC), commonly used for controlling process variability in manufactured goods and services industry, could be appropriate statistical tools for assessing and monitoring changes in soil quality (Figure 1).

In control charting for soil quality assessment, distinction must be made between statistical control limits, computed on the basis of statistical procedures, and target control limits based on acceptance or sufficiency standards. For instance, the mean of a data population describing a soil property might be in statistical control, i.e. lying between an upper control limit (UCL) and a lower control limit (LCL), usually set at 3-sigma values, but it might still be falling below a critical threshold value indicating marginal suitability. In this sense, standards of soil quality are needed to determine what is good or bad and find out if a given soil management system is functioning at an acceptable level of performance (Doran and Parking 1994). The UCL and LCL for soil quality

Table 1. Agriculture as a hierarchy of systems and sequence of assessment approaches
Tabla 1. Ordenamiento de la agricultura en sistemas jerárquicos y secuencia de sistemas de medición.

HIERARCHICAL LEVEL	UNIT	INDICATOR	APPROACH/TECHNIQUE
Land management system	Soil unit	Soil property	Quality control charting (SQC)
Cropping system	Land parcel or field	Crop yield	Yield gap analysis (YGA)
Farming system	Production unit or farm	Input/output ratio	Energy balance analysis (EBA)
Agricultural sector system	Region or nation	Partial indexes 1. agrodiversity 2. system efficiency 3. land resource base 4. food security	Aggregated sustainability index (ASI)

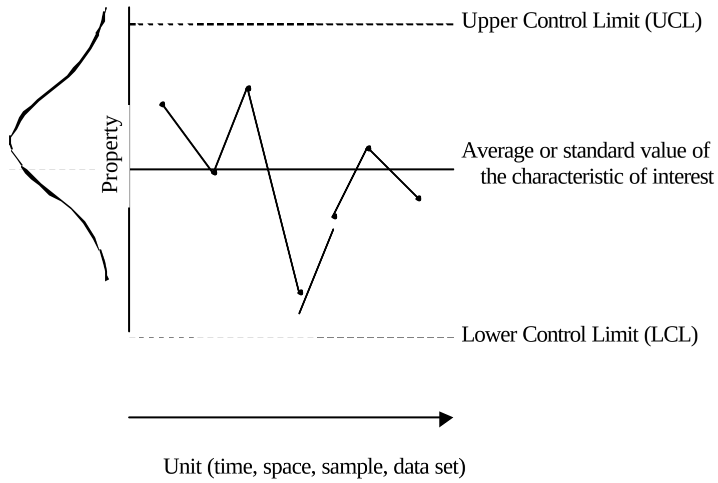

Figure 1. Basic form of a statistical quality control chart (after Ryan 1989; Larson, Pierce 1994)
Figura 1. Forma básica de una carta de control estadístico (según Ryan 1989, Larson, Pierce 1994)

assessment and for making decisions about land management should be based on known or desired tolerance levels, or derived from the mean variance obtained from past performance data (Larson, Pierce 1994).

Case study (Iran)

The SQC technique was applied to a large data set from the Marvdasht plain, a semi-arid intermountain basin at 1500m elevation, located in the Fars province, the heart of the ancient Persian Empire, in southwest Iran. Soils are mainly calcareous and saline Aridisols, locally associated with weakly developed Entisols. The annual rainfall is 150-200mm. The mean annual temperature is 17°C, with hot summers and cold winters (Moameni 1999). This area has been cultivated for centuries with irrigated wheat, causing substantial changes in soil quality. In recent times, farming has been considerably intensified to meet increasing food demand, with massive application of agrochemicals and heavy mechanization. This has led to severe land degradation, including fertility depletion and soil compaction, and raised the issue of sustainability of the modern land management and land use system. To assess the severity of land degradation, a systematic soil sampling scheme was carried out on a 500x500m grid basis, with a total of 2100 observation points. At each grid node, composite samples were taken from topsoil (0-25cm) for organic carbon determination, together with other properties influenced by soil management such as total nitrogen, available phosphorus, available potassium and bulk density. The sampling grid was laid on top of a semi-detailed soil map at scale of 1:50,000 and, for each soil map unit, a set of 20 grid point data was randomly selected as a statistically representative subgroup of the data population with normal distribution, for statistical analysis and control charting (Moameni, Zinck 1997).

Figure 2 shows the X-chart for soil organic carbon. The mean values of all 13 subgroups considered, representing 13 soil map units, fall between the upper and lower control limits. Statistically, the soil organic carbon property is under control and its variability has stabilized at 3-sigma level. The dispersion of the subgroup means around their average value (0.79%) is relatively small, indicating that similar management practices could be applied to all soil map units to maintain the current status of organic carbon. But the statistical control does not reveal whether the present level of organic carbon is suitable for profitable, sustained performance of the crops grown in the area, because the control limits do not correspond to target values. The current average of 0.79% is far below the acceptance value for such a dynamic, management-dependent soil property as organic carbon is. Even the UCL of 1.03% is not close to the adequacy level

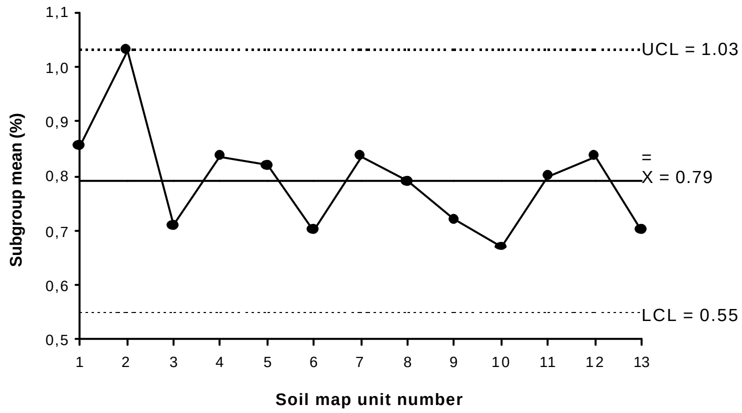

Figure 2. X-chart based on statistical limits for soil organic carbon (Moameni, Zinck 1997)
Figura 2. Carta X basada en límites estadísticos para carbono orgánico del suelo (Moameni, Zinck 1997).

required for good performance of wheat, the main staple crop in the area.

To transform the control chart from statistical into target-oriented, fertility sufficiency standards for wheat production were selected from the literature (Sys *et al*. 1991). To construct the X-chart of organic carbon for wheat production, the values of 0.8% and 2% were adopted as lower and higher acceptance limits, respectively (Figure 3). Subgroups 3, 6, 9, 10, and 13 fall below the LCL, while other subgroups lie just on or close to the LCL. All these soil units are out of sustainability control, reflecting poor land management and exhausting land use. The soil organic carbon balance is out of control. Only, soil unit 2 has organic carbon content suitable for sustained wheat production.

Partial Conclusion

SQC is a useful technique to evaluate the control exerted by specific soil properties on the sustainability of a given land use type and land management system in individual soil units. Control charting can only be applied to individual soil properties, as the latter have different UCL and LCL. Statistical limits are adequate to monitor the behavior of a data population over time, but must be replaced by acceptance/sufficiency standards for sustainability assessment. A relevant limitation of SQC is that large data sets are needed to allow for random subgroup data selection from the whole population and check for nor-

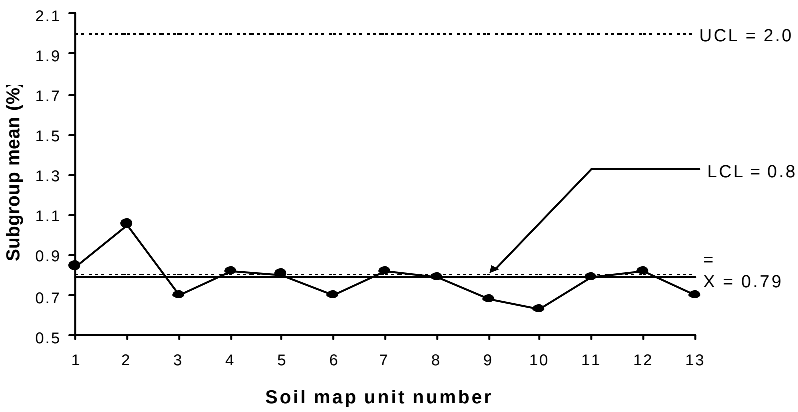

Figure 3. X-chart based on acceptance limits of soil organic carbon for wheat production (Moameni, Zinck 1997)
Figura 3. Carta X basada en los límites aceptables para carbono orgánico en la producción de trigo (Moameni, Zinck 1997)

mal distribution of the data.

THE CROPPING SYSTEM: YIELD GAP ANALYSIS

Approach

A cultivated field in a farm production unit is generally composed of several soil units. Property differences between soil units are often blurred by the application of blanket management practices to a specific crop over the whole land parcel. Thus, the cropping system is an appropriate scale to assess sustainability within the hierarchy of systems constituting the agricultural activity. Yield is a good indicator of crop productivity, which allows us to evaluate both the biological and the economic sustainability of a cropping system. It is rare to obtain a maximum yield from a given tract of land due to a variety of constraints, such as weed invasion, inappropriate fertilization, pests, diseases and mismanagement. As a result, there is often a gap between the actual crop yield and the expected yield. Yield gap analysis (YGA) allows to measure the distance from real field yields to potential yields, identify causes of the gaps, and formulate strategies to raise farmers' yields to higher sustainable levels of cropland productivity. Yield gap has been proposed as a suitable indicator of sustainable land management (Bindraban *et al.* 2000; Dumanski, Pieri 2000).

Conceptual models of the factors that cause and explain yield gaps have been developed (Gomez 1979; De Datta 1981; Tang *et al.* 1992; Ye, Van Ranst 2002). Figure 4 shows such a conceptual model (Fresco *et al.* 1994), depicting the gaps between calculated potential yield, maximum yield from research station and actual farmers' yield. Both biophysical and socio-economic factors are invoked to explain the gaps.

To analyze yield gaps, first yield levels must be established, including calculated, experimental and actual farm yields. A variety of models has been applied for predicting crop yields, including statistical, deterministic, stochastic and empirical models. Among these, deterministic simulation modeling constitutes an interesting approach, which allows us to establish consecutively decreasing predicted yield levels by stepwise increasing crop production constraints (e.g. water, nutrients, farming practices). An example of a deterministic model is the World Food Studies (WOFOST) approach (Driessen, Van Diepen 1987), which is used to simulate crop growth of annuals under different levels of production. Crop yields from non-bookkeeping farmers are usually obtained by harvesting and weighting the crop production of an exactly measured area (crop cutting) over a number of years.

Case study (Kenya)

Yield gap analysis was applied to a data set from Kenya, collected at the Embu Regional Research Center farm, located at 1510m eleva-

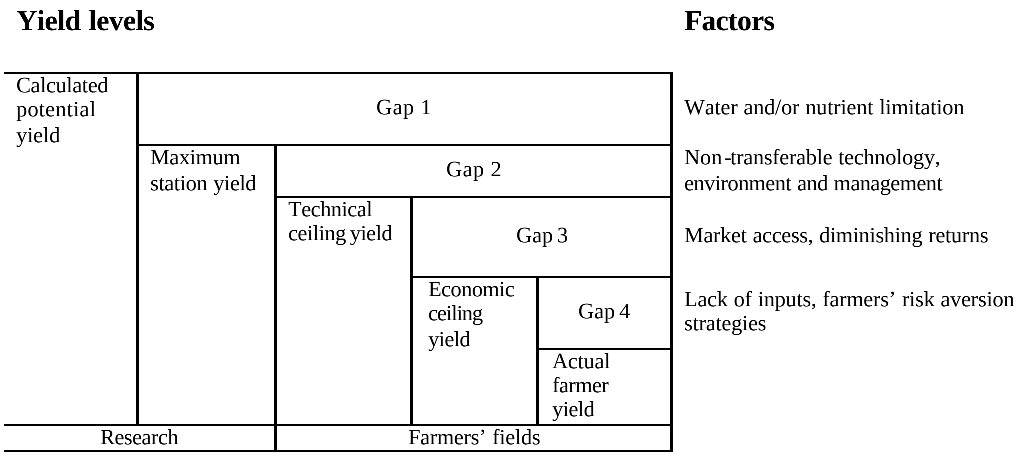

Figure 4. Conceptual model of yield gaps (Fresco *et al.* 1994)
Figura 4. Modelo conceptual de las deficiencias de rendimientos (Fresco *et al.* 1994)

tion on the eastern footridges of Mount Kenya (Wokabi 1994). The average annual rainfall of the area is 1250mm, distributed over two rainy periods per year (610mm in season I from March to July and 400mm in season II from October to January). The mean annual temperature is around 18-21°C. Soils are mainly clayey Humic Nitisols (Ustic Palehumults), developed from weathered phonolites, with moderate fertility. The land use is predominantly smallholder farming. The main food crops include maize, beans and bananas. The only cash crop is coffee. Each household has a few stall-fed dairy cows. Maize being the main staple crop has been selected to conduct the yield gap analysis.

Yield levels

Experimental maize yield data were obtained from a time series of fertilizer trials conducted during the period 1986-93 (Wokabi 1994). The WOFOST model was used to calculate potential and water-limited yields for the same period. Water-limited production corresponds basically to rain-fed farming and is within the reach of farmers when applying appropriate management practices. Actual farm yields were provided by crop cutting, when the maize was ready for dry harvesting, on 10x10m plots randomly distributed on farmers' fields during the period 1992-93. The average values of the potential, water-limited, experimental and farmers' yields are respectively 12.9, 5.8, 4.5 and 4.1 t ha^{-1} for the two rainy seasons combined of the period 1986-93.

The calculated potential yields for season I in the 1986-93 period are fairly uniform, with a mean of 13.3 t ha^{-1} and a coefficient of

Table 2. Nature and magnitude of maize yield gaps at Embu (1986-93) (Wokabi 1994)
Tabla 2. Naturaleza y magnitud de los déficit de rendimientos de maíz en Embu (1986-93) (Wokabi 1994)

Type of yield	Grain yield t ha^{-1}	% of potential yield	Magnitude of yield gap t ha^{-1}	Magnitude of yield gap %	Yield gap No.
Season I					
Potential yield	13.3	100			
Water-limited yield	5.8	44	7.5	12	1
			1.1	9	2
Experimental yield	4.7	35	0.6	23	3
				15	
Farmers' yield	4.1	31			
Potential yield	13.3	10		18	
Experimental yield	4.7	33	8.6	3	4
Water-limited yield	5.8	38	1.7	41	5
Farmers' yield	4.1	25			
Season II					
Potential yield	12.5	100			1
Water-limited yield	5.8	46	6.7	11	
			1.6	6	2
Experimental yield	4.2	34	0.1	38	
				2	3
Farmers' yield	4.1	33			
Potential yield	12.5	100		19	
Experimental yield	4.2	34	8.3	8	4
Water-limited yield	5.8	46	1.7	41	5
Farmers' yield	4.1	33			

variation of 1%. The calculated water-limited yields for the same period reveal a slightly higher coefficient of variation of 19%, with a mean of 5.8 t ha^{-1}. In season II, the calculated potential yields have a mean of 12.5 t ha^{-1} and a coefficient of variation of 1%. The calculated water-limited yields have a coefficient of variation of 49% and a mean of 5.8 t ha^{-1}. The large coefficient of variation in season II may be attributed to higher inter-annual moisture variations. The experimental maize yields for season I over a period of six years, at 50% probability, are estimated to be 4.6 and 3.7 t ha^{-1} with and without fertilizer application, respectively. For season II, the data are 3.4 and 2.1 t ha^{-1}. Farmers' yields varied between 2.5 and 3.8 t ha^{-1}, with a mean of 3.4 t ha^{-1} for season I. In season II, the range was 3.8 to 5.6 t ha^{-1} and the mean was 4.7 t ha^{-1}. In general, inter-annual variations are not excessive, so that mean values can be used for yield gap analysis.

Yield gaps

For the period 1986-93, which can be considered a medium-term investigation period, the magnitude of the yield gaps decreased in the following order: yield gap 4> yield gap 1> yield gap 5> yield gap 2> yield gap 3, for both seasons I and II (Table 2).

Yield gap 1 refers to the difference between the calculated potential and water-limited yields (116% and 129%). The major factor causing the yield gap is moisture limitation. In the calculation of the potential yield, it is assumed that moisture availability is optimal. If the rainfall is sufficiently high and well distributed, the yield gap can be small and may even be negligible in exceptionally good seasons. This gap can be reduced with farming practices that facilitate the efficient utilization of the available moisture in a given environment. Such practices include timely land preparation, planting and weeding, combined with applying compost or animal manure to improve soil structure, biological activity and, consequently, moisture storage capacity.

Yield gap 2 refers to the difference between the calculated water-limited and experimental yields (23% and 38%). In the computation of the water-limited yield, it is assumed that the only limiting factor for crop growth is the availability of moisture supplied from rainfall, as occurs in rain-fed agriculture. Under experimental rain-fed conditions, the crop growth may be constrained not only by limited rainfall but also by insufficient inputs (e.g., fertilizers and manure), weeds, pests and diseases. This gap is relatively small, meaning that there is limited room to increase experimental maize yields at Embu, even when optimal external inputs are applied.

Yield gap 3 addresses the difference between experimental and farmers' yields (2% and 15%). Low crop performance at farm level may be caused by many factors, including non-application of fertilizers, losses due to pests and diseases, destruction of the crop by birds and wild animals, among others. It is possible to decrease this yield gap by timely and better land preparation, applying the right types and quantities of fertilizers and manure, carrying out adequate pest and disease control, early planting of the appropriate maize varieties and proper weeding. These remedial activities should be supported by technical assistance, credit facilities and price policies that encourage farmers to produce higher maize yields under sustainable conditions.

Yield gap 4, which measures the difference between calculated potential and experimental yields (183% and 198%), is of considerable size and reflects the decisive effect of insufficient rainfall on lowering the yields.

Yield gap 5, corresponding to the difference between calculated water-limited and farmers' yields (41% and 41%), might be the most relevant of all and, from the sustainability point of view, more significant than yield gap 3, which measures the lacking behind of farmers' yields in relation to experimental yields. The water-limited yield is a realistic target yield for rain-fed farming, achievable when proper inputs and appropriate management practices are applied. Therefore, yield gap 5 signals the size of the effort necessary to elevate farmers' yields by a magnitude of approximately one-third above the current level, which would make farming activity sustainable.

Partial Conclusion

Increase in food production can be achieved by either expanding the area under cultivation and/or raising the yields from the already cultivated land. In most countries, there is limited scope for expanding cultivated land, since unused land is diminishing or is of marginal quality or just unsuited for agricultural purposes. Although there are possibilities of developing cropping activities in areas of low potential, such lands are usually fragile and susceptible to environmental degradation when subjected to external stress such as agricultural mismanagement. This means that farmers should strive to ensure that each piece of land under cultivation produces the maximum yield possible. In the pursuit of producing maximum yield from a parcel, high doses of inorganic fertilizers, pesticides and insecticides are needed. Unbalanced application of these inputs has the risk of destroying the natural ecosystem and, consequently, the sustainability of land productivity. Therefore, maximum sustainable yield, not maximum possible yield, should be aimed at (Schaller 1993). The yield gap analysis does not indicate by itself what yield level is sustainable, but points at levels of crop productivity higher than farmers' yields, that are achievable with additional inputs and improved management practices. It allows us to identify residual yield opportunities and fix target levels. If the farmer can raise the yield to a higher level, his/her farming activity will become more profitable and therefore more sustainable.

THE FARMING SYSTEM: ENERGY BALANCE ANALYSIS

Approach

One or more cropping systems, sometimes combined with other activities such as livestock or handicraft, can be viewed at the level of a production unit (a farm) as a farming system or, in more general terms, as an agricultural system. A sustainable agricultural system is politically and socially acceptable, economically viable, agrotechnically adaptable, institutionally manageable, and environmentally sound, according to the six-pillar model (Smyth, Dumanski 1993; Farshad, Zinck 2001). Satisfying all these sustainability requirements and the relevant analytical criteria is a complex endeavor; so complex that it may never be implemented for any one system or region. Less comprehensive methods of sustainability assessment, which focus on a particular facet, are more practical to implement, although they might result in greater uncertainty about the overall sustainability of the agroecosystem (Zinck, Farshad 1995).

The energy balance approach allows us to approximate the complexity of a farming system by expressing inputs and outputs in the same unit and making them therefore comparable for assessing sustainability. Agroecosystems depend on both ecologic and agricultural forms of energy. The ecologic energy includes solar radiation for photosynthesis and appropriate atmospheric conditions, while the agricultural energy includes biologic (e.g., labor, manure) and industrial components. When a natural system, capable of producing a certain amount of energy-containing biomass, is converted into an agroecologic system, the natural capability limit is often exceeded by adding energy inputs. The greater the input of external energy, the more the natural capability of the system can be exceeded, and the less sustainable the system becomes. Because of this relationship, the agroecosystem's energy balance ratio is a relatively comprehensive indicator of its sustainability. Since energy use data are often difficult to obtain or lack accuracy, the energy balance analysis (EBA) requires cross checking through multiple interviews and direct *in situ* measurements, such as crop cutting in a farmer's field for yield estimation.

Case study (Iran)

The case study was developed in the Hamadan-Komidjan area, a high plateau encased in the Zagros mountains at 1750m elevation, in the Hamadan province of western Iran (Farshad, Zinck 2001). Climate is semi-arid steppic, with mild summers and very cold winters. The mean annual rainfall is 320-350mm and the mean annual temperature is 11^{o}C. Most agricultural activities are carried out on shallow to moderately deep Xerochrepts. Wheat is the main crop produced in the area. Traditional and modern agriculture is practiced, although traditional farming is steadily disappearing.

Modern agriculture

Modern farming systems are characterised by the use of water emanating from deep wells and artificial dams, improved seeds, machinery (at least tractors), chemical fertilizers,

Table 3. Direct energy consumed by the mechanized wheat system (Farshad, Zinck 2001)
Tabla 3. Energía directa consumida por el sistema de mecanizado de trigo (Farshad, Zinck 2001)

Activity	Time (hr/ha)	Number of treatments	Fuel used (L/ha)	Energy value	Total required energy (Gj/ha)
Plowing	5	2	40	42.7 Mj/L	3.416
Leveling	1	1	10	42.7 Mj/L	0.427
Sowing	1	1	15	42.7 Mj/L	0.640
Irrigation	7	5-6	150	42.7 Mj/L	35.227
Harvest	2	-	40	42.7 Mj/L	1.708
Transportation	-	-	5	42.7 Mj/L	0.213
Labor	110	-	-	1.9 Mj/hr	0.210
Total	126	-	260	-	41.841

herbicides, and pesticides. The introduction of new sources of energy, technology, and machinery has changed the relationship between inputs and outputs, when compared to the traditional production system. Crop production, animal husbandry, and rural industries are no longer interdependent activities at farm level, as was the case in traditional agriculture.

Modern farming in Iran is based on a set of highly mechanized operations, which consume large amounts of energy in terms of labour and use of machinery. Energy consumed for mechanized wheat production (41.841 + 10.464 = 52.304 Gj/ha) is approximately half the energy produced (99.5 Gj/ha), which yields an input/output ratio of roughly 1 to 2 (Tables 3, 4 and 5).

Traditional agriculture

Traditional farming includes the use of animal-drawn wooden ploughs, local seeds, ghanat (underground tunnels), cheshmeh (springs) and/or harvested runoff water, and the absence of agricultural machinery and chemicals. Radiocarbon dating of a soil buried under excavated spoil material at a ghanat mound revealed that the tunnel intercepting the piedmont aquifers to conduct water to a nearby irrigated oasis, was at least 700 years old (Farshad, Zinck 1998).

A traditional production unit is a complex system of interrelated activities carried out by a household. It includes three main components: crop farming, animal husbandry, and handicraft production. Functional integration and temporal distribution of the activities make it necessary for all family members to participate full-time throughout the year. Oxen, cows, sheep, goats, hens, and pigeons are common. Milk products, eggs, meat, flour from wheat and barley, vegetables, fruits, leather, and wool are produced. The large variety of products generated helps mitigate risks from climatic (e.g., drought) to economic (e.g., fluctuations in the world market price).

Traditional agriculture consumes little

Table 4. Indirect energy consumed by the mechanized wheat system (Farshad, Zinck 2001)
Tabla 4. Energía indirecta consumida por la producción de trigo mecanizado (Farshad, Zinck 2001)

Activity	Amount (kg/ha)	Energy value	Total required energy (Gj/ha)
Nitrogen (N)	34	75 Mj/kg	2.550
Phosphorus (P)	48	13 Mj/kg	0.624
Insecticide	1	180 Mj/kg	0.180
Seed	250	18 Mj/kg	4.500
Machinery	30	87 Mj/kg	2.610
Total	-	-	10.464

Table 5. Energy output of the mechanized wheat system (Farshad, Zinck 2001)
Tabla 5. Producto energético del sistema de trigo mecanizado (Farshad, Zinck 2001)

Output	Yield (kg/ha)	Energy value	Energy output (Gj/ha)
Wheat (grain)	3750	14 Mj/kg	52.5
Straw	4700	10 Mj/kg	47.0
Total	-	-	99.5

energy (6.061 Gj/ha), while producing a large amount of energy (46.838 Gj/ha). This equals an input/output ratio of 1 to 8, much better than the 1 to 2 ratio of the mechanized system (Tables 6 and 7). If it is assumed that the 1:8 ratio of the traditional system represents the threshold of sustainability in this region, then the mechanized system approaches the realm of unsustainability. However, the latter produces twice as much wheat as the former and is thus better able to satisfy, at least in the short term, the growing market demand. Unfortunately, heavy machinery used in modern agriculture causes severe soil compaction, which will ultimately lead to yield decline. Simulation modeling predicted wheat yield reduction in the order of two tons per hectare, as a consequence of the effect of mechanization on the deterioration of soil porosity (Farshad *et al*., 2000).

Partial Conclusion

Energy balance analysis has the advantage of expressing all input and output parameters in the same unit. This allows us to establish input/output ratios and compare different farming systems in quantitative terms for assessing their sustainability. Energy flow might be the basis on which economists and environmentalists examine an agricultural system, but it addresses only a limited number of the criteria included in the six-pillar model. A more holistic approach to assess the sustainability of farming systems would require the combined implementation of complementary techniques to secure transversatility through the pillar model.

Table 6. Energy input of the traditional wheat system (Farshad, Zinck 2001)

Tabla 6. Consumo de energía de un sistema tradicional de producción de trigo (Farshad, Zinck 2001)

Input	Energy value	Amount/ha	Total required energy (Gj/ha)
Labor	2.1 Mj/hr	330 hours	0.69
Oxen	2.9 Mj/hr	190 hours	0.56
Machinery	0.4 Mj/L	60 L gas-oil	0.024
Fertilizer	60 Mj/kg	50 kg	2.99
Manure	1 kj/kg	1600 kg	0.002
Seed	14 Mj/kg	130 kg	1.795
Total	-	-	6.061

THE AGRICULTURAL SECTOR SYSTEM: AGGREGATED INDEX

Approach

All farming systems together operating in a region or on a national territory form an activity or production sector -the agricultural sector- the sustainability of which can be assessed using a large range of indicators to secure that all relevant aspects be covered. For the sake of coherence, indicators can be organised in families of criteria reflecting the biophysical, agronomic, social, economic and political components of the agricultural sector. At this upper level of the agricultural systems hierarchy, four criterion domains are relevant, namely agrodiversity, agrosystem efficiency, use of the land resource base, and food security. Appropriate indicators to measure these criteria include: (1) for the agrodiversity: index of crop dominance, crop agrodiversity factor, genetic variability, surface variability; (2) for the agrosystem efficiency: yield and yield gap, cost-benefit ratio, parity index; (3) for the use of the land resource base: a set of ratios such as land availability/land demand, land demand/cultivated land, cultivated land/deforested land, degraded land/cultivated land, cultivated land/inhabitant, irrigated land/irrigable land; and (4) for the food security: per-capita production index, agricultural population/total population, export/import, and food production/food supply.

Individual indicators or partial indexes shed light on the sustainability of particular components or features of the agricultural sec-

Table 7. Energy output of the traditional wheat system (Farshad, Zinck 2001)

Tabla 7. Producto energético de un sistema tradicional de trigo (Farshad, Zinck 2001)

Output	Energy value	Amount/ha	Energy output (Gj/ha)
Grain (wheat)	14 Mj/kg	2000 kg	28.438
Straw	9 Mj/kg	2000 kg	18.400
Total	-	-	46.838

tor, but are limited for evaluating the whole. There is thus a need for integrating partial indexes describing individual indicators into more comprehensive sustainability expressions. The overall sustainability of the agricultural sector at national level can also be assessed using an aggregated index computed by averaging the normalised values of selected indicators. Such an index would be able to approximate with one single quantitative figure the level of sustainability of the agricultural sector at a given moment and monitor its evolution over time, considering all the reservation involved in such an over-simplification. This kind of approach was applied in the Venezuelan case study (Berroterán, Zinck 1997, 2000).

In the attempt to quantify the level of sustainability/unsustainability reached by the Venezuelan agriculture at any time over the last two to three decades, indicators provided with time series of data larger than 20 years were selected to estimate partial indexes. A time span of 20 years corresponds approximately to the long term of sustainable land management (>25 years) according to Smyth and Dumanski (1993) and is intermediate between the terms established by Lal *et al.* (1990) for the sustainability of agricultural productivity (5-10 years) and that of environmental stability (50-100 years). In the present case, only a few indicators satisfied the recording time requirement. The partial indexes describing them were normalized between 0 and 1 relative to their maximal values. An aggregated index of sustainability was generated for consecutive years by averaging the partial indexes, following the approach implemented by Hansen and Jones (1996) for farming systems. The arithmetic mean of the normalized partial indexes describing the indicators represents a rough but reasonable approximation of a generalized sustainability figure. The mean values of the sustainability index for intervals of two and five years, respectively, were represented graphically to highlight the evolution trend of sustainability over time.

Case study (Venezuela)

Venezuela is located in northern South America. About 80% of the country lies below 400m elevation, with temperatures above 25°C and seasonal rainfall regime. A large part of commercial agriculture takes place in the Llanos plains north of the Orinoco River, especially the production of cereals including maize, rice and sorghum. Nearly 85% of the GNP is derived from oil exploitation and mining. Because agriculture generates only 5% of the GNP, a substantial part of the food must be imported.

Individual indicators and indexes signal that the Venezuelan agriculture tends towards unsustainability: lowindex of crop dominance (0.06), low crop agrodiversity factor (0.24), insufficient variation of crop groups over time (0.23-0.30), low performance of the principal crops in relation to their potential productivity (0.43) in spite of increased production/ha (0.25-0.5), low income/cost ratio (1.1-1.28), low parity index (0.6-0.75), unfavorable land availability/land demand ratio (2.4), deficient land use for provision of food demand, low cultivated surface per inhabitant (0.08 ha), unfavorable cultivated land/deforested land ratio, low irrigated land/irrigable land ratio (0.22), high degraded land/cultivated land ratio (0.76), insufficient food production in relation to demand (<0.5) with negative growth rates, low export/import ratio (0.19), low stability of the index of cereal production per capita, low proportion of agricultural population (0.09) with negative growth rate.

Six of these indicators are supported by long-term data records (>20 years), including the proportion of agricultural population, the relative index of cereal production per capita, cereal yield, total food production, agricultural surface area, and agricultural surface per inhabitant. They were used to establish an aggregated sustainability index (ASI) for intervals of two and five years. Index values for two-year intervals resulted highly variable, limiting the reliability of such data to establish a regression model at the confidence level of 95% and making it necessary to increase the level to 99% in order to include all the available information in the confidence interval. Such high index variability over time reflects low stability of the national agricultural system and constrains its sustainability. Index values calculated for intervals of five years were less variable over time and could be adjusted to a linear regression with negative slope (ASI = 13.8583-6.657968 * year) (Figure 5). The former

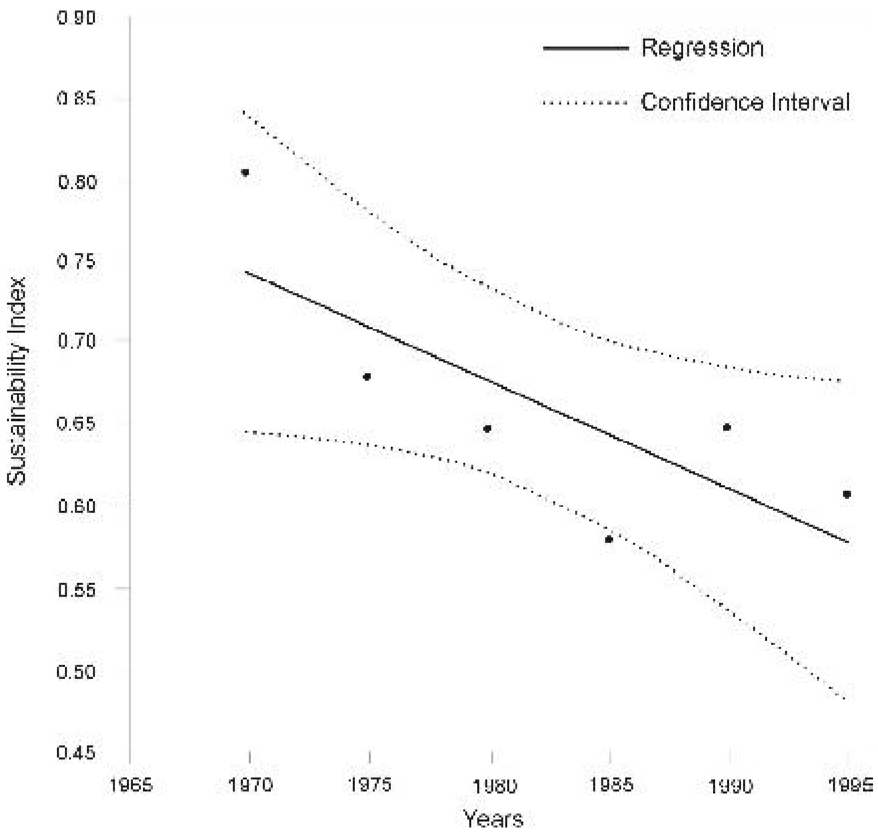

Figure 5. Aggregated sustainability index of the agricultural sector, Venezuela ($r^2 = 0.62$) (Berroterán, Zinck 2000)

Figura 5. Indice de sostenibilidad agregada del sector agrícola de Venezuela (Berroterán, Zinck 2000).

suggests that a five-year interval is a minimum to evaluate sustainability trends over long periods (>25 years) and improve estimates for future years. However, the analysis of interannual variability remains relevant for short-term stability assessment.

The degree of sustainable development can be expressed in terms of probability classes, such as strongly sustainable (>0.70), weakly sustainable (0.59-0.70), and not sustainable (<0.59). According to this criterion, agricultural sustainability in Venezuela was strong until the mid-1970s and became weak afterwards. The tendency of agricultural sustainability to deteriorate over time cannot be mitigated if the prevailing conditions of cereal mono-cropping, land degradation, low economic efficiency, and low levels of production in relation to crop potential despite high farming input, do not change.

Partial Conclusion

In spite of its obvious inherent limitations, a simple aggregated index can provide useful insight on the level of sustainability reached by the agricultural sector at regional and national level and help detect changes over time. Component indicators must be chosen according to data availability, data sensitivity to temporal changes and the capacity of the data to describe quantitatively the behavior of the agricultural activity as a whole. The index needs refinement by integrating additional indicators and by allocating differential weights to the indicators to properly reflect their relevance and dynamics.

GENERAL CONCLUSION

Agriculture is a hierarchy of systems, the sustainability of which can be assessed by means of single indicators or a combination thereof. In this paper, several comprehensive methodological approaches, combining indicators, were applied to four scalar levels of the agricultural activity, including the land management system, the cropping system, the farming system, and the agricultural sector system.

The appropriateness of quality control charting for assessing the sustainability of the land management system is improved when acceptance/sufficiency standards are used as thresholds, instead of the customary 3-sigma statistical limits. In the Marvdasht case (Iran), physical, biological and chemical soil properties have severely deteriorated because of century-long mono-cropping of wheat. Control charting revealed that organic carbon content, while under statistical control, is largely out of sustainability control because modern agriculture neglects regular manure application.

Yield gap analysis, as applied to the Embu case (Kenya), shows that farmer maize yields lie substantially behind experimental and calculated yields. The largest gaps are between calculated potential and experimental yields (mean=191%) and between calculated potential and calculated water-limited yields (mean=123%). This reflects the negative effects of rainfall insufficiency, inappropriate fertilization, poor control of pest and disease outbursts, and other poorly conducted management practices. The water-limited yield is a realistic target yield for rain-fed farming, achievable when proper inputs and management practices are applied. In general, the yield gap analysis does not indicate by itself which yield level is sustainable, but signals residual yield opportunities which can make farming activity more profitable and therefore more sustainable.

The energy balance analysis developed for the Hamadan case (Iran) has the advantage of expressing all input and output parameters in the same unit. Input/output ratios allow us to compare the performance of different farming systems. The longstanding traditional farming system with a 1:8 ratio looks more sustainable than the modern system with a ratio of 1:2. But mechanized agriculture produces higher yields and is thus better able to satisfy, at least in the short term, the growing market demand. This highlights that the energy balance analysis alone cannot address all the facets of agricultural sustainability and must be combined with other techniques to secure a more holistic approach.

Finally, an aggregated index was used for assessing the sustainability of the agricultural sector at national level. Refined algorithms, allowing to allocate differential weights to individual indicators or partial indexes, are not yet available. However, in the case study of Venezuela, a simple aggregated index, based on the mean of normalized indicators, shows clearly that the sustainability of the agricultural sector system has steadily declined over the recent decades.

Much effort is still needed to integrate the methodological approaches in one coherent framework allowing to navigate through the hierarchical levels of the agricultural macrosystem and to take into account the many requirements involved in a holistic model of sustainability.

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