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Biophysical, chemical and socio-economic indicators for assessing agricultural sustainability in the Chinese coastal zone

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Abstract

Agricultural sustainability depends to a great extent upon the maintenance of soil health. There is no single measurement that can be made for its quantification although certain soil biophysical and chemical characteristics are found to be key potential indicators of soil health. An agricultural sustainability index (ASI) is proposed to measure agricultural sustainability as a function of biophysical, chemical, economic and social indicators.

It was tested on a regional dataset from China. It showed marked changes in sustainability over a 9-year period and between regions within the coastal zone. This index appears promising for assessing agricultural sustainability. It permits the comparison of relative sustainability of different agroecosystems and can be used to compare agricultural sustainability across regions, although care must be taken in the choice of rating scale for the component indicators and further research in this is needed. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Increasing human population, declining resources, social instability, and environmental degradation pose serious threats to the natural processes that sustain the global ecosphere and life (Costanza et al., 1992; Pierce and Warford, 1993). Global climate change, depletion of the protective ozone layer, serious declines in species biodiversity, and degradation and shrinking of productive agricultural land are among the most pressing concerns associated with our technological search for a higher standard of living for an ever growing human population (Doran and Safely, 1997). Past management of nature to meet the food and fibre needs for ever-increasing populations has taxed the resilience of natural processes to maintain global balance and the cycling of energy and matter. The challenge ahead in sustaining life on earth will require new vision, with holistic approaches for agroecosystem management. Meanwhile, one cannot manage if one cannot measure. Thus, a research challenge facing agriculture is to determine the key indicators for measuring the impacts of agricultural policy reform and practices on agricultural sustainability.

Agricultural sustainability depends to a large extent upon the maintenance or enhancement of soil health. There is yet no general agreement as to how the soil health concept should be interpreted or precisely defined, let alone quantitatively measured. It cannot be directly measured from the soil alone but can be inferred from soil characteristics and soil behaviour under defined conditions and certain soil quality

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characteristics are found to be potential indicators of soil health. Overexploitation of soils for over three decades has resulted in fatigue in the intensive agricultural production systems worldwide and a steadily declining trend in productivity is witnessed in such systems. The declining trend in rice (*Oryza sativa*) productivity was first noticed in long-term experiments especially with rice-wheat (*Triticum aestivum*) in India (Nambiar and Ghosh, 1984; Nambiar, 1995) and rice–rice production systems in the Philippines (Flinn and de Datta, 1984; Cassman and Pingale, 1995). It is therefore of utmost importance to identify the soil characteristics that demonstrate changes in soil health which may eventually be considered as soil health indicators for assessing agricultural sustainability. Barnett et al. (1995) reviewed various aspects of agricultural sustainability including total factor productivity (TFP) indices, output/input ratios together with many soil health factors. They examined the role of externalities like acidifying inputs from the atmosphere and increasing levels of heavy metals such as cadmium contamination from the atmospheric inputs — the externality of an industrial process but one for which agriculture must bear a cost. Similarly, agricultural sustainability was reviewed by Rainer and Welham (1995). These authors found the Tornqvist–Theil index to be the most suitable for assessing agricultural sustainability. Sarrantonio (1991) identified several soil parameters for assessing agricultural sustainability. These parameters include soil components such as base line characteristics (soil series, depth, texture, slope, etc.), antiquality factors (salinity, heavy metals, pesticides carryover, etc.), soil erosion potential, chemical/mineral (total carbon and/or labile carbon, pH, total N and/or NO_3–N, P, K, micronutrients, other cations), physical characteristics (water infiltration rate and/or permeability, water stable aggregate size distribution, penetrometer resistance) and biological characteristics (microbial respiration rate and/or biomass, soil enzyme activity, earthworm abundance and/or diversity, etc.). Steiner and McLaughlin (1992) provide a model describing the TFP index as a measure of the total value of the outputs (TVO) relative to the total value of the inputs (TVI). This index value may vary widely depending upon the fluctuations of prices of inputs and outputs and may not reflect the biological sustainability of the production systems. Herdt and Steiner (1995) identified three dimensions that should be considered: biological/physical, economic and social.

Many scientists have proposed soil quality indicators and suggested a minimum dataset (MDS) of soil health (Larson and Pierce, 1994). The basic set of soil qualities of Doran and Parkin (1994) was adopted by the National Nature Science Foundation of China and supported the programme, ‘soil quality change and sustainable systems’ in 1999. A meeting of experts of this programme was held in October 1999, at which time a set of various soil attributes which responded to land management and which varied in space and time were proposed. Considering sustainable agriculture in China and elsewhere in the world, preliminary indicators were developed for assessing agricultural sustainability. The preliminary indicators meet the following suitability criteria.

1. Social and policy relevance (economic viability, social structure, etc.).
2. Analytical soundness and measurability.
3. Suitable for different scales (e.g. farm, district, country, etc.).
4. Encompass ecosystem processes and relate to process oriented modelling.
5. Sensitive to variations in management and climate.
6. Accessible to many users (e.g. acceptability).

Quantitative assessments of sustainability require consideration of the many functions that agroecosystems fulfil, their variations in time and space and opportunities for modification or change. Criteria are needed to evaluate the impact of various practices on the quality of air, water and food resources and the environment. Threshold values for key indicators must be established, understanding that these will vary depending upon the specific soil function of greatest concern and the agroecosystem or landscape within which the assessment is being made.

It may be seen from the suitability criteria of preliminary indicators that two different approaches are possible for assessing agricultural sustainability — one approach is based on measured variables and the other based on management practices. Various scoring “points” could be assigned to management practices that have a positive impact on soil health, and negative scores to practices that lead to deterioration in soil health. A management practices-based index will rely on the perceptions of the individuals determining

the soil health index values. Hence, there is much scope for wide variation depending upon the differences in perceptions of the individuals concerned. The index based on measured variables is less subjective but still has an element of opinion involved as to whether a given parameter is inherently "good" or not. The index based on measured variables requires more time, equipment and money than a management-based index. However, there is an initial need to identify and standardise the soil parameters that demonstrate changes in soil health for assessing biological sustainability before integrating with economic and social components. Erosional hazards, waterlogging, salinity, sodicity and acidity are often found to be the major causes of productivity decline. Yet, among the physical, chemical and biological properties, chemical properties are often found to demonstrate rapid changes in soil health, while the changes in physical and biological properties are relatively slow. In spite of the complexity involved in the measurement of soil health, it is possible to develop an index based on soil health and social, management and economic components which can adequately compare agricultural sustainability across areas and times.

A method is proposed here for the quantitative measurement of agricultural sustainability and which is described and then applied to data from the Shangyu model farm in the Zhejiang coastal zone of China. The data for this farm were available for a broad selection of the component indicators proposed below for three different regions, east, middle and west, and for two different years, 1990 and 1999.

2. Materials and methods

2.1. The components of the indicator

A more extensive set of indicators including not only biophysical and chemical, but economic and social as well can be used to determine sustainability in a broader sense. These are the following.

- Crop yield

  Long-term crop yield trends to provide information on the biological productive capacity of agricultural land and the ability of agriculture to sustain resource production capacity and manage production risks.

- Agricultural nutrient balance

  Excessive fertiliser use can contribute to problems of eutrophication, acidification, climate change and the toxic contamination of soil, water and air. Lack of fertiliser application may cause the degradation of soil fertility. The parameters of agriculture nutrient balance are gross nutrient balance (*B*) and input: output ratio (I/O). Gross nutrient balances of the total quantity of N, P and K, respectively, applied to agricultural land through chemical fertilisers and livestock manure, input in irrigation, rain and biological fixation minus the amount of N, P and K absorbed by agricultural plants, run-off, leaching and volatilisation.

- Soil quality

  Soil quality indicators include physical properties (e.g. soil texture, soil depth, bulk density, water holding capacity, water retention characteristics, water content, etc.), chemical properties (e.g. total organic C and N, organic matter, pH, electrical conductivity, mineral N, extracted P, available K, etc.), and biological properties (e.g. microbial biomass C and N, potentially mineralisable N, soil respiration, biomass C/total organic C ratio, respiration: biomass ratio, etc.).

- Agricultural management practices

  Management and the type of fertilisers and irrigation systems will affect the efficiency of fertiliser, pesticide and water use. Agricultural management indicators here include efficiencies of fertiliser, pesticide, and irrigated water uses.

- Agri-environmental quality

  These agri-environmental indicators provide information on environmental impacts from the production process. Degrees of soil degradation and water pollution are included. The degree of soil degradation is measured by the effects of water and wind erosion, salinisation, acidification, toxic contaminants, compaction, waterlogging and declining levels of soil organic matter. The quality of surface, ground and marine water is measured by concentrations in weight/litre of water of nitrogen, phosphorus, dissolved oxygen, toxic pesticide residues, ammonium and soil sediment.

- Agricultural biodiversity

  Biodiversity of plants and livestock used for agricultural production is important to conserve the agroecosystem balance. However, the dependence

on a limited number of varieties and breeds for agricultural production may increase their susceptibility to pests and diseases. Biodiversity measurement is reflected by the total number of varieties/breeds used for the production of major crops/livestock, and the number of animals and microorganisms in the production.

- Economic and social

  Aspects and sustainable agriculture sustainability of agroecosystems is reflected not only in environmental factors but also in economic soundness and social considerations. These aspects are included as real net output (real value of agricultural production minus the real cost), and the change in the level of managerial skills of farmers and land managers in income and farming practice.

- Agricultural net energy balance

  Agriculture not only uses energy (sunlight and fossil fuels) but also is a source of energy supply through biomass production. In this paper our interest mainly concerns the measurement of energy input associated with the agricultural use of fossil fuels per unit of output (energy I/O).

2.2. A quantitative assessment of agricultural sustainability

An index, agricultural sustainability index (ASI), for assessing agricultural sustainability using the broad set of biophysical, chemical, economic and social indicators can be developed as

$$\mathrm{ASI} = N \times Y \times S \times M \times Q \times B \times I \times E \qquad (1)$$

Table 1
Categories, indicators and rating system used to calculate ASI

Category	Indicator	Rate		
		Low: 75	Medium: 85	High: 100
Agricultural nutrient balance	*B* (kg/ha)	<0	0–100	>100
	I/O	<0.75	0.75–1.0	>1.0
Crop yield	Yield	Less than average yield	Average yield	Greater than average yield
Agricultural management	Fertiliser use efficiency (%)	<75	75–85	>85
	Irrigated water use efficiency (%)	<50	50–75	>75
Agri-environmental quality	Soil erosion *t* (soil/km^2)	>500	500–50	<50
	Soil saline content (mg/kg)	>3	3–1	<1
Agricultural biodiversity	The number of varieties/livestock	<50	50–100	>100
	The number of organism	<500	500–1000	>1000
Economic and social viability	Income per labour ($)	<800	800–1000	>1000
	Real net output per unit land ($/ha)	<750	750–1125	>1125
	Cultural level	Less than middle school	Middle school	Greater than middle school
Net energy balance	I/O of energy	<1	1	>1
Soil quality	Clay content (%)	<15 or >40	27–40	15–27
	Soil depth (cm)	<50	50–100	>100
	Bulk density	Greater than average for textural class	Average for textural class	Less than average for textural class
	Available water capacity (cm/cm)	<0.11	0.11–0.15	0.15
	Organic matter (%)	<2	2–5	>5
	pH	<6.1 or >7.8		6.1–7.8
	Permeability (cm/h)	<0.15 or >5.0	0.25–1.5 or 1.5–5.0	0.25–1.5
	EC (mS/cm)	>16	8–16	<8
	CEC (cmol/100 g)	<7	7–16	>16

where N is the agricultural nutrient balance, Y the crop yield, S the soil quality, M the agricultural management, Q the agri-environmental quality, B the agricultural biodiversity, I the economic and social aspects of sustainable agriculture and E is the agricultural net energy balance.

Each category contains indicators (Table 1), each of which is rated from low to high, with 100 as the maximum. The calculation of ASI is a three-stage process.

1. Determine a rating for each indicator.
2. Calculate a rating for each category.
3. Obtain an overall ASI for each agroecosystem by multiplying the eight category ratings.

3. Results

For the Chinese data the ASI index was evaluated individually in 1990 and 1999 for each of the three regions and a ratio of ASI for 1999/1990 was calculated. The results are shown in Table 2. Agricultural sustainability ratings were higher for both years in the eastern part than in the middle and those for the middle were higher than those for the western parts of the farm indicating a regional decline in sustainability. The ASI ratio showed the same pattern of decline. It may be concluded that lower agricultural sustainability is an indication that the agricultural ecosystem lost productivity and that the ecosystem has been degraded in the west since 1990. In the middle region some evidence of a sustainability increase compared to the east was apparent. The index however is dependent upon the categories chosen for the ratings of the individual indicators, and still needs to be tested for its statistical properties and its robustness to different agro-ecological and socio-economic extremes.

Table 2
Mean ASI, and the ratio of agricultural sustainability in 1999/1990 for each region of Shangyu model farm

Region	ASI in 1999	ASI in 1990	Ratio[a]
East ($n = 50$)	80	75	1.07
Middle ($n = 29$)	75	60	1.25
West ($n = 45$)	53	55	0.96

[a] Ratio of ASI in 1999 to that in 1990.

4. Discussion

The TFP index currently in vogue is based on the measurement of the TVO in relation to the TVI. This index may vary widely depending upon the fluctuations in costs of inputs and outputs and the choice of baseline prices. It may not, therefore, assess accurately the status of biological sustainability of the system which is the basic component of soil health. Other indices have used only biophysical measures and do not permit comparisons over different regions, agroecosystems and management practices. Hence, there is a great need to develop an index which adequately incorporates all these components: socio-economic, biophysical and chemical parameters. The latter are greatly influenced by socio-economic status and social change. The ASI proposed here integrated all factors: biophysical, chemical, economical and social. Nevertheless, care should be taken in the choice of rating scale for the component indicators. Extreme situations would result in values at extreme ends of each scale and this would lead to some component indicators influencing the ASI more than others. More research is therefore needed. There also exists an element of judgement since the index value includes socio-economic factors, the criteria of which differ from region to region. Nonetheless, the ASI proposed in this paper quantified the relative sustainability of agroecosystems and is a valuable first step in incorporating socio-economic factors to the agricultural sustainability debate.

Future efforts should focus on a more thorough characterisation of expected values of agroecosystem properties. The optimal range or threshold levels of various soil properties in respect of one group of soils may not be optimal for another group. There arises, therefore, the need for determining the optimal range values for all important soil biophysical and chemical properties for different soil groups. These optimal ranges can then be integrated with socio-economic factors into a single index value as in the present case and which can compare soil health and agricultural sustainability across diverse sites over time.

5. Conclusions

A review of existing methods for assessing soil health and agricultural sustainability was presented.

An attempt was made to incorporate social and economic factors with biophysical factors to produce a new ASI. Tests of this index on regional Chinese data showed realistic results. Further research to test the ratings used for the component indicators is needed so that comparison of ecosystems and regions can be made with confidence.

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