Farm Level Indicators of Sustainable Land Management for the Development of Decision Support Systems

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1. Abstract

Appropriate methodologies that encompass biophysical and socioeconomic criteria for evaluating sustainable land management (SLM) are still in the developmental stage. Data and information, required for sustainability assessment, are generally unavailable, sparse and/or incomplete. This study makes use of the Framework for Evaluation of Sustainable Land Management (FESLM) to determine the environmental, economic and social sustainability of major farming systems in the Prairie Region of Western Canada. A case study approach was used in implementing the FESLM methodology. Data and information were drawn from spatial land resource databases, long-term research, on-site measurements, questionnaires and extensive producer interviews.

Local knowledge as obtained from questionnaires and interviews were valuable for addressing gaps in information requirements for sustainability assessment. The role of indicators, identified by agricultural producers in conducting FESLM-based sustainability assessments, are discussed. Preliminary indications are that producer decision-making characteristics (e.g. strategic and operational decisions on the basis of parameters such as moisture availability at seeding, agricultural commodity prices, etc.) are a critical component of sustainability across farming systems. Commonality in the decision-making characteristics of SLM practices across farming systems facilitates the conceptualization of agricultural decision support systems. A framework for mobilizing the information obtained from the project level into a decision support system for sustainable land management is discussed.

2. Introduction

Farmers are faced with a variety of critical sustainability considerations, and implement numerous strategies to address the issues arising from these considerations. The main characteristic of these considerations is that they are primarily tactical ones, e.g. whether it would be cost effective to apply fertilizers at recommended rates if spring soil moisture is less than optimal. This study draws on the common characteristics in farmer strategies that make their production system sustainable. This approach to identifying sustainable land management (SLM) characteristics of different farming systems recognizes the diverse ways of achieving sustainability within a given region. Commonalties in the characteristics of each sustainable farming system can serve as indicators of SLM. Moreover, they can be distilled for use as guides for other producers who wish to achieve sustainability in their farming practices. A focus on common SLM characteristics facilitates the structuring of decision support systems for evaluating sustainability or for aiding farmers and their advisors in achieving sustainable land management systems.

2.1 Sustainable Land Management

This study is conducted within the context of a precise definition of SLM and an associated methodology, the Framework for Evaluation of Sustainable Land Management (FESLM). SLM is defined (Dumanski and Smyth, 1994) as a system that combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously:

- maintain or enhance production/services [productivity];
- reduce the level of production risk [security];
- protect the potential of natural resources [protection];
- be economically viable [viability];
- be socially acceptable [acceptability].

These five objectives (productivity, security, protection, viability and acceptability) constitute the pillars of SLM. The FESLM is a logical pathway analysis procedure to guide the evaluation of land use sustainability through a series of scientifically sound steps (Smyth and Dumanski, 1993). It is comprised of three main stages: i) identification of the purpose of evaluation, specifically land use systems and management practices; ii) definition of the process of analysis, consisting of the evaluation factors, diagnostic criteria, indicators and thresholds to be utilized; and iii) an assessment endpoint that identifies the sustainability status of the land use system under evaluation.

3. Methodology

Farm management systems in Saskatchewan, Canada, were classified by length and diversity of crop rotation (fallow-based; diversified annual grains; diversified grain-forage) and level of chemical input (high, medium, organic) into a 3 x 3 matrix. Approximately thirty farms were selected to represent these farming systems and the major soil-climatic zones, soil textures and soil landscapes of the agricultural area of the province (Foster 1994).

The main areas of research consist of: determination of indicators and decision making characteristics from farmer knowledge; biophysical and economic modelling; determination of weed and insect populations and dynamics; and assessment of wildlife habitat. Farmer-based operational indicators pertinent to each of the pillars of sustainable land management were obtained using farm-level land use mapping, administration of a series of questionnaires and in-depth interviews of a subset of contact farmers.

The impacts of land management practices on soil loss from wind and water erosion, surface and groundwater quality, nutrient balance and yield variability are being determined using the Erosion Productivity Impact Calculator (EPIC) model for quantifying relationships between crop yield and erosion, productivity and fertilizer needs (Williams 1990, Williams et al. 1990, Kiniry et al. 1995). Simulations using the EPIC model, extending for 25 years or more, are being conducted on the farms under study using their current farming practices. Economic modeling consists of simulating each management system using combined cost of production data, farmer risk preferences, and simulated EPIC crop yield and soil degradation data.

The impact of cropping systems on residual weed communities and on insects (pests and beneficial) is being determined by surveys to determine species number (diversity), species abundance (density), species uniqueness (indicator), and species life history (strategy).

The effects of differing land management practices on the quantity and quality of natural upland and wetland habitats, biological diversity of several taxa, and productivity of selected organisms representing various taxonomic groups is being evaluated through field surveys of the areal distribution and quality of natural and agricultural habitats.

Information obtained from each component of the overall project will be combined to conduct an FESLM-based assessment of sustainability for each farming system. This will entail determining the objective and means of farm enterprises and proceeding to independently evaluate sustainability for a series of factors of the physical, biological, economic and social environment using a suite of indicators and criteria. The EPIC model, economic analysis, field surveys and farmer-knowledge will serve as the basis for determining the sustainability of land management systems.

3.1 Framework for DSS development

In order to provide reliable SLM decision support the characteristics that constitute sustainable land use within given agro-environmental and socioeconomic conditions need to be known. An efficient way to achieve this is by identifying sustainable land use systems, characterizing the attributes that make them sustainable, and identifying criteria by which to measure the status of these attributes in other land use systems.

Results to date from the Saskatchewan SLM studies provide useful information on the relative impacts of different management systems on sustainability. Although modeling efforts can show differences between components of the study matrix, the data and results obtained do not sufficiently identify which farmers within a given system are likely to succeed in achieving sustainability. This latter information is linked to farmer knowledge, and particularly to farmers' decision making characteristics regarding the strategies they implement to attain sustainability.

The analysis to date indicates that those farmers with a wider range of choices and a flexible, responsive, approach to signals from their environment are more likely to maintain or achieve a sustainable land management system than those rigidly following a particular management system. Indicators identified by farmers for the farming systems under study are given in Table 1.

A DSS that reflects farmer decision making characteristics needs to integrate farm-level indicators obtained from farmer knowledge, with land resource data as well as biophysical and economic models. It should provide a means for identifying sustainable land management systems for specific agro-ecosystems.

Procedures required for the development of an FESLM-based DSS consist of: i) development of information and knowledge bases drawn from SLM studies; ii) structuring the information and knowledge bases into relationships between pertinent FESLM parameters; and iii) coding information and knowledge bases, plus associated relationships into a computerized DSS.

Table 1. Sustainable land management indicators as identified by producers through questionnaire responses and in-depth interviews.

FESLM Pillars	Indicators by Farming System		
	High Input	Moderate Input	Organic
Productivity	– Soil fertility trends – Crop yield response – Availability of labour	– Yield trends – Adoption of new technologies & techniques – Crop variety availability & performance	– Length of rotation – Weed management – Crop variety availability & performance
Security	– Economic status – Yield trends – Weather trends	– Time required in mastering new techniques – Catastrophic weather/weather trends	– Resource potential of land – Soil moisture at seeding – Weather trends
Protection	– Degradation risk – Extent of crop cover	– Degradation trends – Length of rotation – Extent of fallow	– Degradation trends – Crop yield trends
Viability	– Cash flows/revenues – Presence of livestock – Management objectives	– Cash flow/revenues – Government programs – Management objectives	– Organic market demands – Extent of value added – Availability of labour
Acceptability	– Personal & family health – Viability of farming	– Availability of services – Off-farm impacts	– Public awareness of organic farming – Viability of farming – Age level of community

3.2 Analytical Tools

The combination of the decision support needs of identified or perceived decision-makers and the FESLM framework provides the necessary structure for developing the requirements definition for a computerized DSS. A preliminary outline of the evaluation factors, information types and analytical tools for consideration in development of requirements definition for the SLM-DSS are given in Table 2.

The components required to construct a DSS for SLM are derived from research methodologies and modelling tools similar to those used in the Saskatchewan SLM study. The analytical tools to assess the status of biophysical or economic factors within a production system generally consist of empirical or process models, with an accompanying demand for extensive data. Land resource data are best represented spatially and therefore require GIS technologies for computerized representation. Heuristic or rule-based knowledge and the development of links between scientific information and local farmer knowledge require the use of expert system technologies with appropriate knowledge representation. A schematic of a DSS for sustainable land management is shown in Figure 1.

3.3 Prototype Expert System for Soil Conservation

A prototype expert system that can contribute to the biophysical module of a DSS for SLM has been developed by AAFC researchers. The objective of the prototype expert system for soil conservation was to integrate farmer knowledge with scientific research for soil degradation - crop productivity relationships. The prototype expert system, SOILCROP, was developed on the premise that innovative conservation farmers are adept in early identification of soil degradation problems and implementing remedial measures. It is recognized that these innovative farmers have intuitively developed and made use of indicators of the status of soil quality on their land to assist them in their diagnosis of degradation problems and choice of management practices.

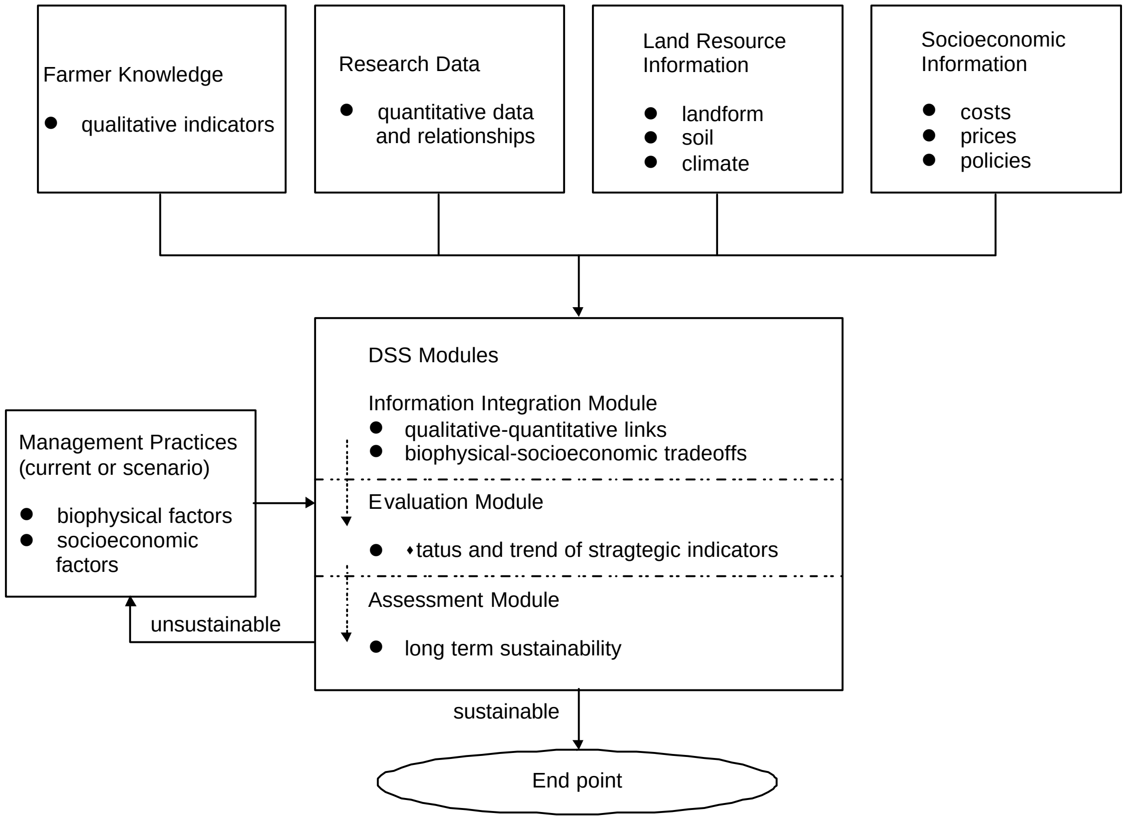
Table 2. Outline of evaluation factors, information types and analytical tools for consideration in development of Requirements Definition for the SLM-DSS

FESLM Pillars	Evaluation Factors	Type of Information	Analytical Tools
Productivity	Production potential	Spatial data	Database/GIS
	Actual production	Measurements	User input
	constraints	Measurements/observations modeled local knowledge	User input models expert system
Security	Yield trends	Spatial & temporal data	Database/GIS
	Weather trends	Spatial & temporal data	Database/GIS
	Constraints	Measurements/observations modeled local knowledge	Statistics models expert system
Protection	Degradation risk	Spatial data	Database/GIS
	Management practices	Observations	User input
	Management-degradation relationships	Modeled local knowledge	Models expert system
Viability	Management objectives	Observations	User input
	Operating costs/ revenues	Measurements	User input
	constraints	Modeled local knowledge	Models expert system
Acceptability	Community constraints	Observation local knowledge	Expert system
	Government policy	Impact assessment observation	Model expert system

Establishing relationships between qualitative farmer knowledge derived from these innovative farmers and quantitative scientific data, involved significant methodological challenges. In the development of SOILCROP, the qualitative knowledge was dispersed among a number of expert farmers and there were gaps or conflicts in the knowledge base. This required extensive knowledge elicitation through interviews, resolution of conflicting information, and validation of the knowledge base with experience from local agronomists.

During expert system development, it was necessary to organize and synthesize the underlying symbolic relationships behind the complexity of such information. This entailed identifying the parameters to be considered, establishing criteria for categorizing identified parameters, indicating the assumptions made in developing criteria, and stating the symbolic relationships as a set of rules for use in the expert system (Gameda and Dumanski, 1997). Such a process revealed the underlying links between the qualitative knowledge base of innovative conservation farmers and the quantitative soil quality information from scientific research. The symbolic relationships obtained from combined farmer knowledge and scientific research sources were used to develop the set of rules which drive and control the expert system. For example, researchers can obtain data on actual topsoil depth and crop yield reductions to derive explicit relationships between them. Qualitative knowledge, however, would entail abstraction of topsoil depth into soil colour, and aggregation of crop yield reductions across seasons, soil types and landscapes to provide heuristic relationships between soil colour and crop response. The precision obtained is more coarse than can be derived from actual data, but this is counter-balanced by a greater ability to apply the knowledge base to a wider set of conditions.

Figure 1. Schematic of a DSS for sustainable land management.



SOILCROP determines the type and level of soil degradation at the farm or field level, associated yield reductions, and remedial management practices. It consists of a spatially referenced map, plus four expert system modules comprising degradation, crop yield, remedial management practices and productivity. The expert system modules consist of rule bases structured from indicators provided by innovative conservation farmers and validated by regional agronomists. Data for the productivity module was obtained from numerous runs of the EPIC process model for a range of crop rotations and tillage practices in a wide selection of agro-environments.

SOILCROP is linked to a land resource database through a geographic information system (GIS) interface to enable input of location specific physical attributes to better define the environmental envelope within which the land use systems operate. A prognostic module draws on modelled output from process models such as EPIC to provide the long term impact of chosen management practices on soil degradation and crop productivity. A schematic of the overall structure is given in Figure 2.

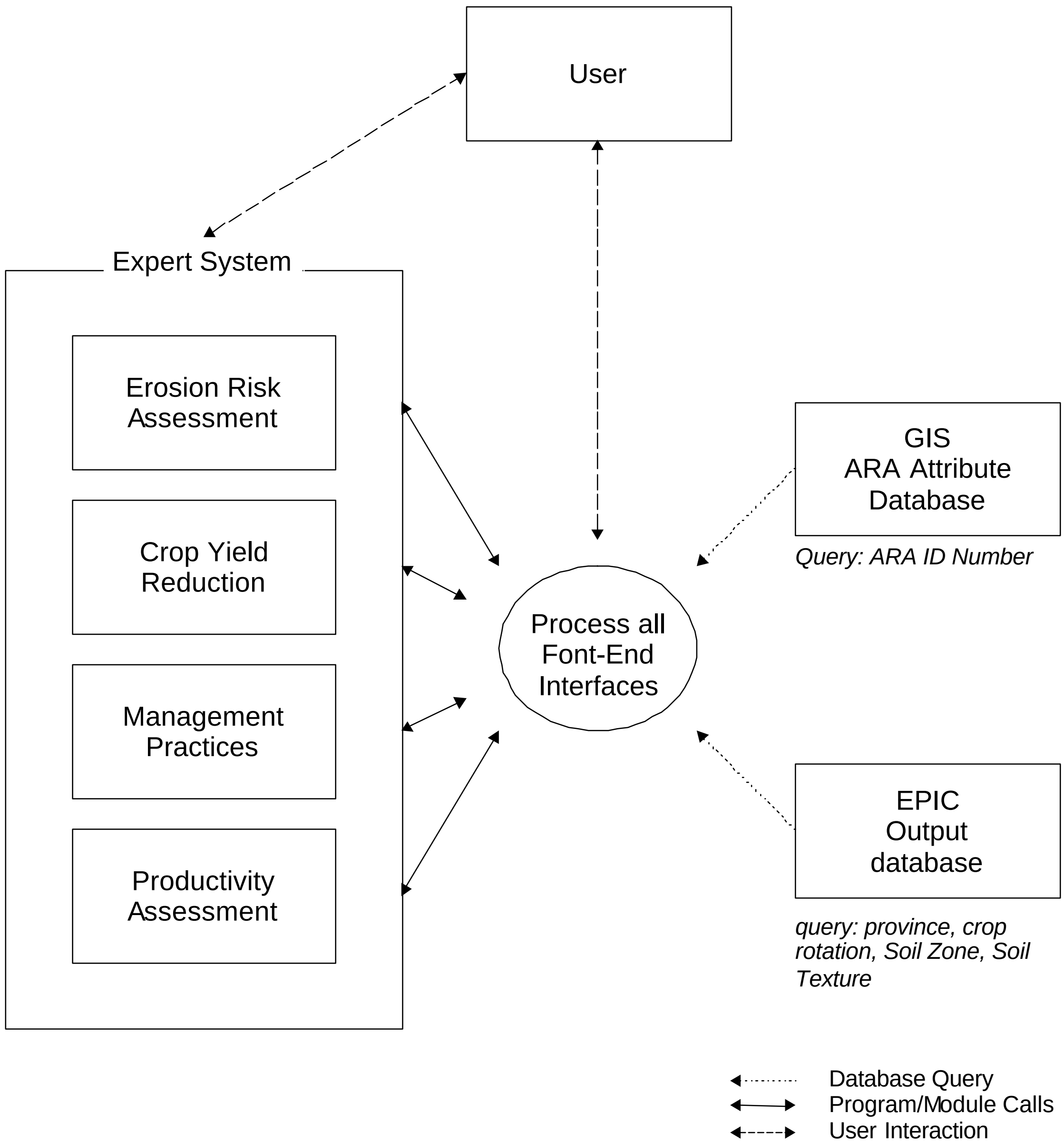


Figure 2. Schematic of structure and data flow of SOILCROP.

4. Discussion

4.1 Application of SOILCROP experience to FESLM-based Decision Support Systems

Information provided by innovative conservation farmers often contains implicit environmental, economic and social criteria for sustainability. For example: the level of degradation and associated yield loss that farmers are willing to internalize before implementing ameliorative practices, the number of years that drought can be tolerated before the systems fail, etc. However, explicit criteria are required for these principles to be applied outside the domains in which they were obtained. Results from the Saskatchewan SLM study are aimed at developing explicit environmental, economic and social indicators and thresholds by which the sustainability of the range of agricultural production systems in different agro-environments can be assessed. This requires that land resource databases be established and mobilized, expert farmer knowledge be obtained, and that biophysical and economic impact models be integrated within an interactive structure. The following discussion describes the process to develop the knowledge base and computer coding components of the DSS.

4.2 Indicator Database

The key to the success of a DSS for SLM is a comprehensive, purpose-oriented database. Extensive soil inventories and considerable volumes of data on agricultural land resources are necessary. These data should be structured into natural biophysical units such as land resource areas (LRAs), whereby each area consists of landscapes with similar ecoclimatic characteristics, land potentials, degradation risk, etc. This store of land-related information should be complemented by long-term research trials on the effects of soil degradation on crop production, and on the effects of various management practices combining crop rotation, tillage, etc. on sustainable agricultural production. These kinds and detail of data are not, however, available in many parts of the world. Moreover, even when available, they need to be aggregated into suitable indicators for purposes of assessing and monitoring the status of SLM objectives. Farm oriented case studies (Dumanski et al. 1995) and research projects similar to the Saskatchewan SLM study are necessary to develop the required knowledge base for DSS development.

One of the objectives for the next phase of the Saskatchewan SLM project is to develop a DSS for SLM evaluation. Data and information obtained from the project will be compiled into databases comprising region-specific evaluation criteria, indicators and thresholds for local applicability. These would then serve as a basis for the development of the DSS for sustainability assessments of farm-level production systems in the Canadian Prairies. Methods for compiling and structuring the database will be similar to those used in the development of SOILCROP. The DSS will be designed as a generic system applicable globally, but structured to draw on region-specific data and knowledge bases.

5. Conclusion

Experience from the development of SOILCROP has shown that the DSS development process is necessarily an iterative one. Incorporation of local farmer knowledge is essential to address data and information gaps, and in determining farm-level SLM indicators. Development of DSS for SLM should aim to follow an approach that combines local knowledge, biophysical and economic models, spatial databases and scientific research to ensure appropriate tools are deployed and all SLM considerations are addressed. The complexity entailed in the DSS development approach described herein reflects research needs for a methodology with a sound scientific basis. Actual development of an operational DSS is in reality a simpler process, that with mobilization of local farmer knowledge, ensures rapid deployment of SLM evaluation applications.

6. References

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