CSIRO PUBLISHING

Australian Journal of Experimental Agriculture

Volume 39, 1999

… a journal publishing papers (in the soil, plant and animal sciences) at the cutting edge of applied agricultural research

www.publish.csiro.au/journals/ajea

All enquiries and manuscripts should be directed to
Australian Journal of Experimental Agriculture
CSIRO PUBLISHING
PO Box 1139 (150 Oxford St)
Collingwood
Vic. 3066
Australia

Telephone: 61 3 9662 7614
Facsimile: 61 3 9662 7611
Email: chris.anderson@publish.csiro.au
lalina.muir@publish.csiro.au

Published by
CSIRO PUBLISHING
in co-operation with the
Standing Committee on Agriculture and Resource Management (SCARM)

Australian Journal of Experimental Agriculture, 1999, **39**, 605–20

A framework to monitor sustainability in the grains industry

R. C. Dalal[AJ], *P. Lawrence*[A], *J. Walker*[B], *R. J. Shaw*[A], *G. Lawrence*[C], *D. Yule*[D], *J. A. Doughton*[E], *A. Bourne*[F], *L. Duivenvoorden*[C], *S. Choy*[A], *D. Moloney*[G], *L. Turner*[A], *C. King*[H] *and A. Dale*[I]

[A] Department of Natural Resources, 80 Meiers Road, Indooroopilly, Qld 4068, Australia.
[B] CSIRO Land and Water, PO Box 1666, Canberra, ACT 2601, Australia.
[C] Central Queensland University, Rockhampton, Qld 4702, Australia.
[D] Department of Natural Resources, Rockhampton, Qld 4700, Australia.
[E] Department of Primary Industries, Emerald, Qld 4720, Australia.
[F] Department of Primary Industries, Rockhampton, Qld 4700, Australia.
[G] Department of Environment and Heritage, Brisbane, Qld 4002, Australia.
[H] Department of Natural Resources, Dalby, Qld 4405, Australia.
[I] CSIRO Tropical Agriculture, Brisbane, Qld 4067, Australia.
[J] Author for correspondence; e-mail: Ram.Dalal@dnr.qld.gov.au

Summary. Community awareness of the sustainable use of land, water and vegetation resources is increasing. The sustainable use of these resources is pivotal to sustainable farming systems. However, techniques for monitoring the sustainable management of these resources are poorly understood and untested. We propose a framework to benchmark and monitor resources in the grains industry.

Eight steps are listed below to achieve these objectives: (i) define industry issues; (ii) identify the issues through growers, stakeholder and community consultation; (iii) identify indicators (measurable attributes, properties or characteristics) of sustainability through consultation with growers, stakeholders, experts and community members, relating to: crop productivity; resource maintenance/enhancement; biodiversity; economic viability; community viability; and institutional structure; (iv) develop and use selection criteria to select indicators that consider: responsiveness to change; ease of capture; community acceptance and involvement; interpretation; measurement error; stability, frequency and cost of measurement; spatial scale issues; and mapping capability in space and through time. The appropriateness of indicators can be evaluated using a decision making system such as a multiobjective decision support system (MO-DSS, a method to assist in decision making from multiple and conflicting objectives); (v) involve stakeholders and the community in the definition of goals and setting benchmarking and monitoring targets for sustainable farming; (vi) take preventive and corrective/remedial action; (vii) evaluate effectiveness of actions taken; and (viii) revise indicators as part of a continual improvement principle designed to achieve best management practice for sustainable farming systems.

The major recommendations are to: (i) implement the framework for resources (land, water and vegetation, economic, community and institution) benchmarking and monitoring, and integrate this process with current activities so that awareness, implementation and evolution of sustainable resource management practices become normal practice in the grains industry; (ii) empower the grains industry to take the lead by using relevant sustainability indicators to benchmark and monitor resources; (iii) adopt a collaborative approach by involving various industry, community, catchment management and government agency groups to minimise implementation time. Monitoring programs such as Waterwatch, Soilcheck, Grasscheck and Topcrop should be utilised; (iv) encourage the adoption of a decision making system by growers and industry representatives as a participatory decision and evaluation process.

Widespread use of sustainability indicators would assist in validating and refining these indicators and evaluating sustainable farming systems. The indicators could also assist in evaluating best management practices for the grains industry.

 10.1071/EA98108

Introduction

The concept of sustainable development has its beginnings soon after World War II (FAO 1946). The United Nations Conference on the Human Environment (1972) and International Union for Conservation of Nature and Natural Resources (1980) proposed that economic development and environmental issues should be integrated to allow for resource conservation for sustainable development. Brown (1981) in *Building a Sustainable Society,* suggested that it would be possible to harmonise the material needs of society and the rational utilisation of natural resources in such a way that environmental pollution would also be minimised. Thus, sustainable development would meet the needs of the present generation without compromising the ability of future generations to fulfil their own needs (WCED 1987, referred to as Brundtland report). Later, the United Nations Conference on Environment and Development (1993) released a document AGENDA 21 on a program for action on sustainable development, which strongly suggested creation of mechanisms to facilitate the active involvement and participation of all concerned, particularly communities and people at the local level, in decision making for sustainable development.

In the context of sustainable farming systems, sustainable development is defined as the use of farming systems and practices which maintain or enhance (i) economic viability; (ii) sustainable use of natural resources; and (iii) the protection of ecosystems which are influenced by agricultural activities (Standing Committee on Agriculture 1991).

Community awareness is increasing about the sustainable use of land, water and vegetation resources but monitoring of these resources for sustainable management is poorly understood. The monitoring process is at best partially developed and mostly untested (Hamblin 1992). A framework needs to be developed to monitor sustainability in the grains industry: (i) to establish a set of sustainability indicators acceptable to growers and develop methods to measure and evaluate them; and (ii) to benchmark environmental and biophysical resources and their utilisation by grain and grain/grazing enterprises.

The framework should be underpinned by a good understanding of the biological, physical, economic and social basis of the grains industry. This will ensure that the management practices applied by industry can be monitored using appropriate indicators against established benchmarks to determine whether they are sustainable both on the farm and beyond the farm gate (Rendell *et al.* 1996). This will require the design of a methodology to develop baseline benchmarks and the application of tools to assist grain growers and the wider industry sector to monitor performance against these benchmarks and against related indicators of sustainability. In this report, we propose a framework to monitor sustainability in the grains industry, set selection criteria for sustainability indicators and a decision making process to evaluate the appropriateness of these indicators to monitor sustainability of farming systems.

A methodology to benchmark and monitor resources of the grains industry

Monitoring and assessment procedures are of little value on their own without preventive, corrective or remedial actions taken, their effectiveness evaluated and stakeholders partnership engendered. A set of steps is recognised for monitoring sustainability of farming systems (Fig. 1).

A framework to monitor resources in the grains industry

A framework is proposed to benchmark and monitor resources in the grains industry. The steps required for achieving these objectives are: economic and environmental awareness, and farm and community benefits analysis of resource monitoring. These should be based on identifying and formulating the issues from biophysical, farm, community and institutional (industry bodies and corporate and government agencies) aspects. Community and stakeholders are involved in identifying appropriate indicators, monitoring resource using indicators, and assessing and evaluating the effectiveness of preventive and corrective/remedial actions taken. Barriers to adoption and/or effectiveness of the indicators to benchmark and monitor sustainability of the farming systems are then identified and the indicators are revised for continual improvement.

The framework to monitor resources in the grains industry (Fig. 1) extends the catchment health monitoring strategy suggested by Walker and Reuter (1996) in that it also includes a continual improvement process in redefining the industry issues as well as revising the sustainability indicators, since economic, community and institutional indicators are continuously changing. On the other hand, the framework used to derive sustainability indicators for forest management provided limited involvement of community groups, and was principally devised by international expert groups (The Montreal Process 1995). The proposed framework at least partly corrected this by actively involving various stakeholders in the grains industry.

The framework to benchmark and monitor the sustainability of the grains industry was developed in a workshop involving grain growers, agribusiness, a catchment group representative, an industry fund provider, education providers, resource managers and research, development and extension personnel representing natural resources, primary industries and environment. The sustainability indicators were presented at the workshop by the expert/interest group, discussed by all participants, and evaluated according to the selection criteria, which was adapted at the workshop from Walker and Reuter (1996). The selection criteria for sustainability indicators are presented below.

Selection criteria for sustainability indicators

Indicators are measurable attributes, which can be used to monitor the condition of natural resource or socioeconomic systems. They may be a single parameter or a combination of weighted parameters. They can be monitored via field observation, field sampling, remote sensing or compilation of existing information (Walker and Reuter 1996). Sustainability indicators are intended to provide a common measure and evaluation of sustainable systems and a process to monitor trends of these systems.

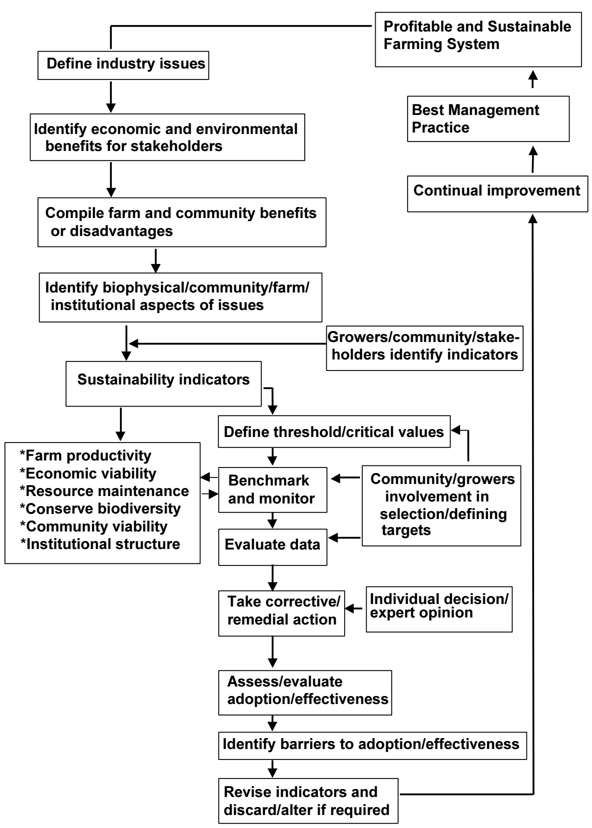

Figure 1. A framework to benchmark and monitor resources of the grains industry.

The main principles underpinning the sustainable indicators were adapted from Dumanski and Smyth (1993) for land management evaluation and The Montreal Process (1995) for the soil and vegetation monitoring. These principles are: (i) to maintain and enhance productive capacity of natural resources; (ii) to conserve and maintain the quantity and quality of soil, water, air, flora and fauna resources; (iii) to minimise production risks associated with climate variability and market forces; (iv) to conserve biodiversity to ensure optimum functioning of global life cycle processes; (v) to ensure economic viability; (vi) to maintain and enhance socioeconomic benefits to the community (social acceptance); and (vii) to encourage legal, institutional, economic and political structures conducive to the sustainability culture.

Indicators to monitor farming systems at both on-farm and off-farm scales are evaluated by rating each one according to the following criteria (adapted from Walker and Reuter 1996). These criteria are rated (scale 0–1) in this report so that the proposed sustainability indicators can be evaluated using a decision support system such as MO-DSS analysis. This means that the grains industry and associated stakeholders can choose their criteria from which the most appropriate indicators can then be selected. This formal and transparent process overcomes some of the emotive attachments to certain indicators and can assist in conflict resolution and negotiation between stakeholders with different interests (Shaw 1997).

The selection criteria to identify, define and select sustainability indicators are (scores from 0 to 1): (i) responsiveness to a change in management (practices) or disturbance over time (0, non-responsive; 1, responsive); (ii) ease of capture (0, extremely difficult, needs specialist training; 1, easy, even for non-specialist); (iii) interpretation against expected or threshold values available (critical value below or above which the system is not sustainable) (0, not available; 1, universally available); (iv) low error associated with measurement (0, extremely high error; 1, extremely low error); (v) stable in short term to enable measurement (0, extreme fluctuation; 1, very stable); (vi) frequency of measurement (0, requires extremely frequent measurements; 1, need not be frequent); (vii) cost of measurement/information capture ($/ha) (0, >$100/ha; 0.1, $90–100/ha; ... 1.0, <$10/ha); (viii) mappable in space and through time (0, not mappable; 1, easily mappable, both in space and through time); (ix) ability to be aggregated (from paddock or site to farm and from farm to catchment, and from catchment to region) (0, extremely difficult; 1, very easy); (x) community acceptance and involvement (0, none; 1, complete or full).

It is envisaged that new criteria may be added, or existing criteria removed by the stakeholders in a particular region. Suggested values of various indicators are available from Dalal *et al*. (1998).

Sustainability indicators for monitoring resources in the grains industry

Indicators of crop productivity

Productivity can be defined in terms of quantity and quality of product per unit of area per unit of time or quantity of product per unit of water used. For example, quantity might be kilograms of wheat grain/ha.year, while quality might be the protein percentage of that grain. The productivity concept can be extended to include dollars earned/ha.year for the grain harvested together with the discount or premium for its protein percentage or dollars earned/ha.year.mm water used.

Products and resources can change in value over time. For example, wheat prices change, as do premiums for protein percentage. A good example of a change in value of a resource is the increase in value of mineral nitrogen derived from Brigalow soils. Initially, after clearing, the supply of mineral nitrogen was thought to be unlimited in terms of crop and pasture growth and little consideration was given to its management. Now it is regarded as a valuable resource because its limitations are controlling productivity.

Because indicators need to be stable from year to year, and because grain prices and quality premiums fluctuate, it becomes easier to develop an indicator based on a physical entity. With crops this is generally grain yield or saleable produce/unit area.unit time. For other vegetation it is total plant biomass/unit area.unit time. Indicators that combine products of value with resources that are limited, valuable or degradable should be the most suitable.

Suitable crop productivity indicators in the grains industry might therefore be:

Crop yield/ha.year. This statistic is a function of great interest to members of the grains/grazing industry and is universally measured. As an indicator it is not robust because of annual climatic variability, but when calculated as a 5-year moving mean it becomes much more meaningful in indicating a trend for a particular grain commodity. It is not possible, however, to convert from one crop to another, for example wheat to soybean or mungbeans.

Percentage of potential yield. This indicator, described by Walker and Reuter (1996), calculates the actual yield/ha as against the achievable yield based on water-use efficiency (WUE) values. This can also be estimated by simulation modelling, such as CERES, PERFECT (Littleboy 1997) or APSIM for various crops and crops grown on different soils. This indicator should be useful in highlighting poor soil fertility and structure, crop management, seasonal effects (e.g. frost), or weed, disease and pest problems in a given year as well as longer-term trends in crop utilisation of available water. A major problem, however, is the large data requirement at the paddock scale and for different crops, if modelled.

Yield/dollar invested in crop. This variable is essentially an indicator of the relative investment value of grain cropping and provides indications as to the likely expansion or contraction of particular grain enterprises. It is most likely to be converted to $ return/$ invested, net return or gross margin. However, it is difficult to interpret threshold values.

Legume : cereal ratio. This is an indicator of nitrogen (N) input into the system through N_2 fixation and the grower’s commitment to sustainable rotations (Herrmann 1994). It is again most likely to be converted to $ return/$ invested, net return or gross margin. Again, it is difficult to interpret threshold or critical values for sustainability of the systems.

Water-use efficiency. Since water is the most limiting resource for non-irrigated grain production, WUE can be a very useful indicator of crop productivity. It is often used as a benchmark indicator against an achievable standard. Water-use efficiency requires measurement of crop available soil water content, which is very difficult at the paddock scale.

Additionally WUE is greatly influenced by various cropping parameters and can be highly variable. For example, Ridge *et al.* (1996) showed that variation in N accumulation in wheat at flowering changed WUE from 3.7 to 10.3. Soil organic carbon and pH also caused differences. On the other hand, sensitivity of WUE to these parameters makes it a useful indicator for monitoring sustainability of the various farming systems.

Water-use efficiency/year. This is an indicator that could be particularly useful in the northern region, where 2 crops per year are possible and opportunity cropping based on rainfall occurrence is practised. It would provide a measure of the utilisation of total annual rainfall and fits well with a systems approach to farming rather than an approach based on an individual crop.

Grain protein. A strong indicator of sufficiency of mineral N supply from soils, particularly in years of high rainfall, a low grain protein indicates possible yield loss. For example, when protein is below 11.5% for wheat, there is insufficient N to optimise yield in that season. Insufficient N can severely limit profitability in good seasons. This indicator has demonstrated a strong declining trend when calculated as a moving mean for areas of Queensland and northern New South Wales. Again, it is prone to seasonal variation.

Percentage of prime hard wheat varieties not achieving prime hard classification. A very strong indicator of fertility decline, previously available from wheat receival depots before deregulation of wheat marketing. It can be accessed from grower's protein records. This indicator demonstrated over a sequence of years how the Central Highlands had the fastest run-down of N fertility of any wheat growing area in Queensland.

Grain nitrogen/ha.mm crop available water. This is another possible indicator of the soil's ability to supply mineral N to crops, particularly in good seasons. Most attributes for this indicator are readily available on-farm, but measuring plant available soil water content and the interpretation of critical values are the main difficulties.

Gross margin/ha.mm of water.year ($/ha.mm.year). With this indicator, crop yield and quality are converted to dollars using standardised prices for commodities for the period over which comparisons are required. It is a good indicator for comparing between crops in terms of dollars earned for water used. Again, like WUE, it is prone to considerable variation.

Gross margin/ha.mm.year is the most integrative indicator of crop productivity, natural resource maintenance or enhancement and economic viability of a farming system. It is responsive to change in management practices or disturbance, and easy to capture (yield or plant biomass, production cost, produce price, rainfall). It can be aggregated from paddock, farm or catchment; threshold or critical levels can be estimated from potential yield; it is relatively stable and inexpensive. This indicator needs to be measured once a season and will have high acceptance in the grains industry.

Indicators of natural resource maintenance/enhancement

Maintenance (and often enhancement) of the natural resource base is fundamental to achieving a sustainable farming system. The use of land and water and the change in vegetation for agriculture inevitably alters the quality and quantity of the natural resource base. Indicators, which can measure such alterations over time, are explained below. They provide measures of sustainability of natural resource use at paddock, farm and catchment scales.

Soil pH. Soil pH as an indicator can provide trends in land resource quality in terms of surface and subsurface acidification, salinisation, structural stability as indicated by exchangeable sodium, limitations to root growth, increased incidence of root disease, biological activity, and nutrient availability [e.g. lower phosphorus (P) availability at either high pH >8.5, or low pH <5; and zinc (Zn) availability at high pH >8.5]. Soil pH trends also indicate changed capacity of the soil for pesticide retention and breakdown as well as the mobility of certain pesticides through soil. These processes affect the natural resource base both on-farm and beyond the farm gate.

Electrical conductivity. Electrical conductivity (EC) is a measure of salt concentration and, therefore, can provide trends in salinity for both soil and water and limitations to crop growth and water infiltration. Along with pH (indicating soil sodicity) it can be a surrogate measure of soil structural decline (e.g. high pH, >8.5 and low EC, <0.1 dS/m leads to unstable soil structure).

Organic matter in the surface soil. Organic matter is fundamental to the maintenance of the soil resource and thus is essential to the optimal functioning of a number of processes important to sustainable farming systems. Soil organic matter is a source and sink of N and partly of P and sulfur (S). It affects micronutrient availability by forming complexes, chelation and production of organic acids, thus altering soil pH. Organic matter is essential for good soil structure (Arshad *et al.* 1996), especially in coarse-textured soils, as it contributes towards both formation and stabilisation of soil aggregates. Other functions include: contribution to cation exchange capacity especially in low activity clay and coarse-textured soils, pesticide degradation, soil fauna and microbial biodiversity (Heal *et al.* 1996; Pankhurst 1997), water retention in sandy and sandy-loam soils, and as a carbon sink to greenhouse gases. Therefore, organic matter content in a soil is considered the foremost indicator of soil quality (Karlen *et al.* 1997) and soil health (Acton and Gregorich 1995). Trends in soil organic matter content provide an integrated measure of sustainable farming systems.

Available plant nutrients. Trends in available plant nutrients, for example N, P, S and potassium, indicate the system's sustainability, especially if the nutrient concentration and availability are approaching threshold values. Long-term nutrient balance of the system (e.g. nutrient input x efficiency of use = nutrient output or removal) is essential to sustainability. Thus, available nutrients are indicators of the capacity to support crop growth, potential crop yield, grain protein content, and, in excess amounts, the potential for environmental hazard (e.g. algal blooms). Trends in available plant nutrients can be discerned from the trends in fertiliser use in the grains industry.

Microbial biomass. Microbial biomass is a labile source and sink of nutrients. It affects nutrient availability and nutrient cycling and is a good indicator of potential microbial activity and capacity to degrade pesticides (Karlen *et al.* 1997). Although useful as a research tool, its cumbersome measurement and variability with short-term environmental conditions makes it questionable as a sustainable indicator.

Soil surface cover. Surface cover by either crop residues or vegetation protects the soil surface from raindrop impact, enhances infiltration, reduces soil erosion and may decrease runoff (Carroll *et al.* 1997). The extent of surface cover, therefore, provides an integrated indicator of physical resource maintenance, organic matter input and even the effects beyond the farm gate. It can be visually assessed or inferred from previous crop yields and tillage practices. It can also be measured by satellite imagery (currently expensive) and, in combination with digital elevation mapping, may provide an indicator of erosion hazard. However, correct timing of monitoring in relation to cropping cycle and erosive rainfall periods is essential.

In the northern region, erosion and runoff are episodic events (Littleboy *et al.* 1997). Due to their episodic nature, it is difficult to accurately discern trends within 3–5 years, although sequential aerial photography or Landsat imagery may provide an indication of the extent of erosion damage. Photographs soon after an event, before cultivation or planting, provide a permanent record of the extent of rilling, broken contour banks and ineffective waterways. Some events of erosion and runoff from paddock or farm need to be measured but this is slow and needs intensive skilled labour. These data may also be supported by measurements of sediment load downstream.

Rooting depth. Rooting depth is a good indicator of plant-available water capacity, subsoil salinity and other root growth constraints in the soil profile. However, it varies with crop type and yield-limiting factors such as nutrients, acidity and crop disease. It is not known whether trends can be discerned over relatively long periods.

Surface crust. Surface crust provides an indication of soil structure decline if it can be quantitatively measured or, alternatively, photographed over time and the extent quantified.

Stream turbidity. Stream turbidity, along with the volume of stream flow provides an integrated indicator of the consequences of land management practices on soil erosion and runoff. Equipment to measure stream turbidity is cheap and easy to use. However, stream turbidity needs to be interpreted in the context of sediment, soil type, and nature of salts in the catchment. Community groups, local government bodies and government agencies can monitor it. Whether long-term trends in erosion and runoff can be discerned from these measurements needs to be examined.

Intact riparian vegetation of a minimum width per unit length of stream. Riparian vegetation provides a filter for runoff and allows deposition of sediments, protects stream banks, and serves as a repository of biodiversity and, in otherwise permanent cleared surroundings, provides shelter to predators.

In-stream macroinvertebrates. In-stream macroinvertebrates have been used as an indicator of biodiversity and environmental pollution in surface water. Waterwatch and state agencies regularly measure their presence. There is a general trend in Australia, and elsewhere, to focus on biological indicators rather than chemical indicators in measuring water health.

Water quality. Water quality is a major issue of community concern and a good indicator of catchment health. Catchment committees, landholders and local and state government agencies monitor water quality. Parameters monitored include turbidity, pH, EC, nutrients (N and P) and pesticides.

In summary, the most appropriate on-farm indicators of natural resource maintenance and enhancement appear to be pH, EC, organic matter, plant- available nutrients, surface cover and surface crust. The off-farm indicators are downstream water quality (flow, turbidity, EC, nutrients and pesticides), and macroinvertebrates in waterbodies and riparian vegetation.

Indicators of biodiversity

The ultimate objective of the conservation of biological diversity is the survival of species (and the genetic variability within those species) and the habitats to support them. Ecological processes and viable populations of species are usually dependent on a contiguous ecosystem or ecosystems of a certain minimum size. Genetic diversity within a species population depends on the maintenance of subpopulations and the existence of ecosystems that cover a large part of their natural range.

Ecosystem diversity. The amount of an ecosystem reserved in some form of protected area (extent of remnant vegetation and reserved remnant vegetation) is a measure of maintaining representative areas of that ecosystem by the community. The fragmentation of remnant vegetation into small pieces may disrupt some ecological processes and the availability of habitat. Such fragments of native vegetation may be too small to maintain viable breeding populations of species. Distances between fragments can interfere with pollination, seed dispersal, and wildlife movement and breeding. Ultimately, excessive fragmentation can contribute to the loss of plant and animal species unable to adapt to these changed conditions.

In areas converted in the past to agricultural purposes, remnant patches of the original native vegetation may provide refuges for many (although not all) components of the original diversity. To illustrate this last point and make it relevant to the northern grains region, State of the Environment Advisory Council (1996) noted that in the last 100 years, 50–75% of the total area has been cleared (percentages will be higher for certain localities); of the remaining native vegetation, the majority is highly fragmented; habitat clearance and/or fragmentation is seen as the greatest threat to biodiversity; 1–12 plant species are threatened (number depends on the locality); and 1–10 vertebrate species are threatened (number depends on the locality). Moreover, countless species of invertebrates have disappeared.

The extent of pest plants and animals, erosion, salinity and acidity, and extent of pesticide and herbicide use and their residues also threaten ecosystem diversity.

Species diversity. Dependent species in remnant vegetation and the status of threatened species provide indicators of species diversity. However, these indicators are costly and difficult to measure.

Genetic diversity. Indicators of genetic diversity include viability of dependent species and habitat monitoring. However, these indicators are slow to respond to changes in biodiversity over time due to disturbance or change in management practices.

To summarise, it is essential that we view remnant patches of vegetation as a valuable resource. It is also essential that we undertake assessments and continue research and long-term monitoring so that any adverse impacts arising from our activities can be detected and redressed through revised codes of practice and management plans.

There is often a need for quick, reproducible assessments of the status of an area, either in relation to conservation or proposed management. Traditionally, these assessments have been done using elements of ecosystems that may or may not represent a true reading of the integrity of that system, but are used simply because they are easy to count or measure (e.g. species and number of vascular plants).

A new technique being developed, known as ‘rapid biodiversity assessment’, uses groupings of species (ecological functional groups) or morphospecies (non-taxonomic species) to compare sites with each other, and against some benchmark state defined independently (Beattie *et al.* 1993). Although this technique is not yet widely accepted, one of its key features is that a non-specialist with minimal training can do the sampling. Possible candidates for the new technique, and their advantages and disadvantages follow: (i) vascular plants—relatively easy to sample and identify; may not respond rapidly to changed conditions; (ii) terrestrial and aquatic invertebrates—respond very rapidly to environmental change (e.g. disturbance) and can be classified into meaningful functional groups; relatively easy to sample but difficult to identify. Often invertebrate numbers are highly variable and huge changes can occur naturally, which makes it difficult to measure the effects due to disturbance or management practices. Moreover, a specialist involvement is essential, as numbers of species are high; hence the need for a morphospecies approach; (iii) vertebrates—not always easy to sample (especially nocturnal species). Spatial scales of distribution may not match those of areas to be assessed. The number of species is relatively low (so identification is easy) but this measure may be of low reliability because of the low number of individuals; (iv) non-vascular plants—little research done to date; some evidence points to their potential as indicators; (v) soil microflora—relatively easy to sample but difficult to identify; some research done but ecological relationships in natural ecosystems still unclear.

Remnant vegetation threatened by introduced and invasive pest plants and animals, pesticide and herbicide drift needs to be protected. It is possible to use remote sensing or aerial photography to record the extent of erosion and salinity which may be a threat to native remnant vegetation.

Indicators of economic viability

Producers can use on-farm economic viability indicators to assess measures of liquidity and solvency, and the profitability of farm business. The following ratios can be used as indicators of business performance: debt/gross income, gross income/total assets, percentage return/assets, percentage return/equity, and interest cover ratio (net income/interest payment). Farm size, enterprise mix, return on assets, disposable farm income, diversification of interests and on-farm/off-farm assets are considered indicators of economic viability.

Farm size. Farm size is an important indicator in terms of its ability to attract services to the locality or region and respond to change. This response to change is very difficult for small farms, which may be short of capital. Large farms are more able to respond to changed market circumstances, seasons, regulation and community expectations. However, it is difficult to aggregate farm size data across regions and industries.

Enterprise mix. Income from grain relative to total farm income reflects the stability of a mixed farming system. It provides options to change in response to market circumstances. However, it is difficult to interpret in terms of sustainable resource use and cannot be aggregated across industries and regions.

Percentage return on assets. This ratio can be aggregated on a regional basis. If it is strong, growers are better placed to manage change proactively. For example, Smith (1993) showed that percentage return on assets declined from 4.7 in the 1982–90 period to 1.9 in the 1990–93 period for the grains industry in the Central Highlands, thus reducing growers' capacity to change. However, it is difficult and expensive to measure.

Disposable farm income. Over a reasonable period, this indicator, adjusted to consumer price index, provides a satisfactory indicator of sustainable systems although threshold values need to be revised regularly. It needs to be considered along with $ return/ha.mm water used.year, an integrative indicator of crop productivity, natural resource maintenance/enhancement, and economic viability.

On-farm/off-farm asset. An indicator of the commitment by the farm business towards sustainable management practices. The grower takes a long-term approach to sustained economic returns since short-term low returns from the farm due to erratic rainfall and/or market forces are buffered by using off-farm assets. Moreover, diversification can lead to a more sustainable business even during times of poor commodity prices.

In summary, disposable farm income including off-farm income and on-farm/off-farm asset over a reasonable period and $ return/ha.mm water used.year provide good indicators of the sustainability of a farming system. These indicators can be aggregated across industries and regions.

Indicators of community viability

Indicators of farm family and rural community health are a combination of statistical analysis and surveys to provide both a condition (snapshot) and trend in community viability (Lawrence *et al.* 1996).

The most pertinent on-farm indicator, disposable income per family unit, is an indicator of both economic and community viability. Total time spent in recreational pursuits by the farm family can be an indicator of community viability. On-farm and off-farm labour, the time the property has remained in the same family, plans for the future of the farm, and participation in educational groups are difficult to interpret against expected or threshold values. It is difficult to capture the data on farm family stress levels. The education level of producers may or may not be strongly responsive to a change in management practices.

The number of people employed in local business, retail turnover of businesses and level of unemployment are appropriate indicators of community viability. Similar to on-farm indicators, both disposable income of the community and time spent in recreational pursuits by the rural community are indicators of community viability. The following indicators are limited by interpretation against threshold or critical levels of sustainability: type and longevity of business, numbers and membership in community organisations, education levels, and income and expenditure by local government.

Indicators of management and decision making, both on-farm and off-farm, include: ability of the farm family to carry out desired management changes; the proportion of families with access to information and technology services and input into information and technology development; and ability of farm family to (over) budget for uncertainty and risk associated with climate variability, market price fluctuations and changes in family circumstances. Another indicator is the percentage of families monitoring their land condition. However, acceptance of these indicators needs to be developed in the user's context.

Selection criteria of community indicators need to be negotiated with growers, stakeholders and the community. Ease of data capture can be high with an appropriate methodology. Responsiveness and cost of monitoring criteria may not be appropriate for community indicators. Improved decision making does not always mean change but it may mean continual improvement. Also, interpretation of an attribute can be based on improvement rather than the threshold value. Initially involving extension professionals experienced in qualitative data collection and analysis can reduce error in measurement.

Indicators of institutional structure

Indicators of institutional structure are designed to assist in determining and monitoring the effectiveness of government, industry and community-based institutional structures that deal with sustainable resource management. They also contribute to an understanding of political efficacy within the grains industry. If there is little interaction between farmers within a region in regard to sustainable management issues, then this suggests there are broader social and economic stresses upon farmers that will influence the ability of strategies developed by the grains industry or by government to affect change.

The context within which these indicators are used, however, is critical. Before they can be finalised, decisions need to be made regarding whether indicators will be used: (i) directly by grain growers to provide a basis for on-farm decision making; (ii) by the regional grains industry as a basis for negotiating reform both within the industry and with other regional stakeholders; or (iii) by government regulatory and support agencies in establishing policies and administrative arrangements, for example, for sustainable land management. The exact nature of the indicators developed will differ depending on the use context.

At an on-farm scale, the indicators are primarily concerned with the awareness by growers of the Environmental Protection Act (EPA) by the authorities/agencies in various states, and involvement with and participation in industry and resource management groups such as the United Graziers' Association, Grain Growers' Association, Farmers' Federation, Landcare and catchment groups.

In response to the Environmental Protection Act 1994 (Queensland EPA 1994), Farmers' Federation developed an Environmental Code of Practice for Agriculture in 1997. Similarly, the Sugarcane Growers in 1998 developed a Code of Practice for Sustainable Cane Growing in Queensland. Also, the Cotton Growers' Association has developed a Code of Practice for safe handling, use and disposal of chemicals for the cotton industry. Although the grains industry does not have a comprehensive Code of Practice for the whole industry, a code of practice has been developed for lupins in Western Australia. Also, a code of practice exists for fumigation and pest control in grains storage and handling.

A comprehensive code of practice needs to be established for the grains industry similar to that in other industries. The industry code of practice demonstrates whether there has been industry action in establishing sustainable practice standards at a regional, state or national level. It could also be used as a basis for policy and administrative reform and for the development of proactive strategies to assist compliance with grower's 'General Environment Duty of Care' under the EPA (Queensland EPA 1994).

On-farm indicators include: number of growers who are members of grains industry groups; and who also belong to resource management groups in their region; number of growers aware of industry codes of practice established under the EPA; and whether growers meet standards set out in codes of practice. However, such codes are voluntary and no auditing system exists. Survey techniques can be used which contain simple 'yes/no' answers or a series of questions and comparisons built into a farmer's monitoring schedule.

Regional indicators include: whether there is an appropriate industry code of practice relevant to the EPA; the percentage of growers aware of the industry code; and the percentage of farms meeting practice standards set out in the industry code of practice. These indicators can be measured by 'yes/no' responses from the industry at the appropriate level by industry-based surveys within a defined region. This figure could also be disaggregated at the subregional level if required. Other indicators for consideration are: percentage of formal Impact Assessment Statements (IAS) with local impacts which adequately deal with the concern of local growers; percentage of IAS which incorporate sustainability indicators for monitoring within their environmental management plans; and percentage of local governments within the region that have adequately negotiated with grains industry regional groups in the development of their planning schemes. National indicators would be an extension of regional indicators (Standing Committee on Agriculture and Resource Management 1998).

While indicators can be established to monitor resource health (Walker and Reuter 1996), the development of strategies for implementing change relies equally on institutional indicators such as those outlined above. Further work will be needed to integrate them with other indicators, particularly in regard to community health and management and decision making.

Evaluating the appropriateness of sustainability indicators

To minimise the problems associated with a linear compilation of scores and to provide a transparent process for stakeholder involvement in determining suitable indicators, a multiple-objective decision support system (MO-DSS) analysis is proposed to evaluate the appropriateness of the sustainability indicators. Using this approach, it is possible to identify groups of preferred indicators that would be more appropriate for a given rank importance order assigned to the selection criteria of the indicators. In addition, the approach allows different interest groups (scientific, extension personnel, farmers and catchment groups) to be involved in the evaluation of the indicators by individually prioritising selection criteria. Involvement at this early stage of the analysis encourages participation and enhances acceptance of the outcomes.

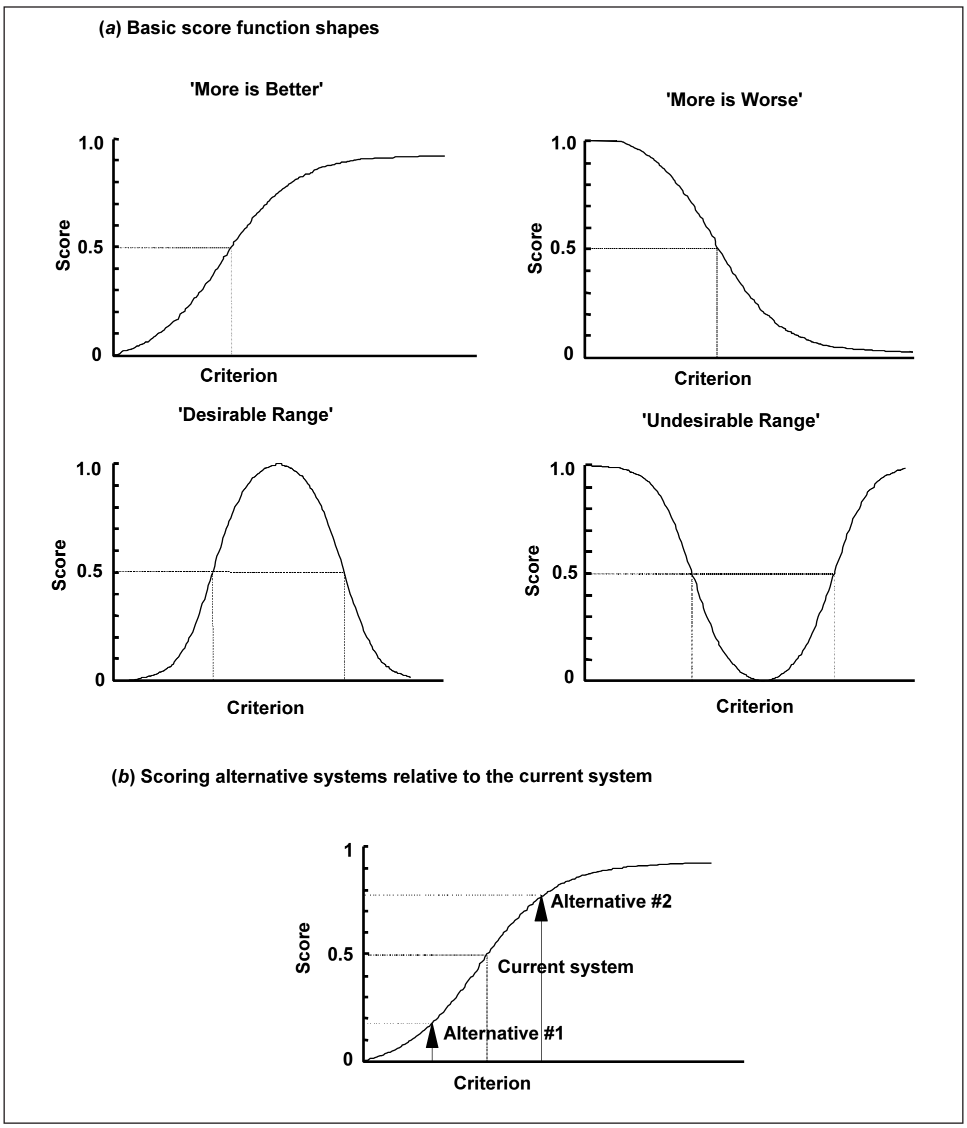

Figure 2. Score functions of the MO-DSS showing (*a*) basic score function shapes, and (*b*) scoring alternative systems relative to the current system (adapted from Yakowitz *et al.* 1993).

A multiple objective approach to the identification of a preferred set of indicators of sustainability involves: (i) identifying appropriate criteria for an indicator; (ii) developing alternative indicators; (iii) evaluating the indicators against each criterion; and (iv) determining an importance ranking for the criteria.

Three scenarios are developed to illustrate the versatility of the proposed approach.

The multiple objective decision support system (MO-DSS) used in the analysis has been developed by the USDA Agricultural Research Service, Southwest Watershed Research Center in Tucson, Arizona.

Overview of the MO-DSS

The MO-DSS proposed for the grains industry and used in this analysis is a method to assist the decision-maker when multiple and possibly conflicting objectives need to be addressed (Lane *et al.* 1991; Yakowitz *et al.* 1992). The decision-maker is presented with a ranking of the alternative options compared to the existing system based on an importance order ranking of the decision criteria. The stakeholders or interest groups may select the importance order. Although primarily used to assist decision-makers to evaluate alternative systems for natural resource management such as tillage practices (Lawrence 1996; Shaw 1997), the MO-DSS was adapted for this application to examine the appropriateness of different indicators of crop productivity.

The decision model of the MO-DSS has 3 subcomponents: (i) the score functions and their shapes; (ii) the calculation of best and worst scores; and (iii) the method of ranking alternatives. A brief description of each of these follows.

Score functions and their shapes. The purpose of the score functions is to scale the decision criteria or attribute from its original units into a dimensionless quantity or score within the range 0–1. This enables all decision criteria to be compared on a common basis. For decision criteria that are expressed in qualitative terms (e.g. aesthetics, wildlife habitat) a user-acceptable index is needed to convert the units of quality to a score value. The score functions are based on the 12 score function shapes proposed by Wymore (1988), reclassified to 4 basic score shapes and combined with decision rules developed by Yakowitz *et al.* (1992). The 4 score function shapes (Fig. 2*a*) are: more is better (MIB); more is worse (MIW*);* a desirable range (DR); and an undesirable range (UDR). Further refinement of each score function shape can be achieved by specifying whether the shape is constrained by an upper and/or lower threshold.

The score functions are set up so that the current management system scores 0.5 as a baseline for each decision criterion. Alternative management systems are then scored relative to the conventional system for each decision criterion (Fig. 2*b*). A system that performs better than the current system will score higher than 0.5, while one that performs worse than the conventional system with respect to the selection criterion will score less than 0.5. All of the alternative options are scored for each criterion to develop a score matrix.

Importance order of criteria. Once each selection criterion is scored, aggregating the scores provides a means of ranking the current and alternative management systems. This is normally done by determining an importance order, allocating weights to each score and then summing the scores to determine the total composite score. However, assigning weights is a difficult and subjective process for the decision-maker and may have a large impact on the outcome. The method of Yakowitz *et al.* (1993) partially overcomes this problem by calculating the best and worst possible scores for all possible weight vectors for an importance order.

Table 1. Scores for indicators of crop productivity

Criteria	Yield	Biomass	Potential yield	Water-use efficiency	Gross margin ($/ha.mm.year)	Grain protein	Grain nitrogen
Responsive	0.7	0.7	0.9	0.9	0.9	0.8	0.9
Capture	0.9	0.5	0.7	0.6	0.6	0.9	0.7
Interpret	0.5	0.5	0.8	0.8	0.8	0.8	0.5
Error	0.7	0.7	0.7	0.6	0.5	0.9	0.8
Stable	0.7	0.7	0.7	0.6	0.5	0.7	0.7
Frequency	0.8	0.7	0.9	0.8	0.8	0.8	0.8
Cost	1.0	0.6	0.8	0.6	0.6	0.8	0.7
Aggregate	0.8	0.9	0.8	0.8	0.8	0.8	0.8
Mappable	0.8	0.9	0.8	0.8	0.8	0.9	0.8
Acceptance	1.0	0.8	0.5	0.6	0.6	0.9	0.7

The MO-DSS initially determines a default importance order based on the slope of the scoring function. This method of determining an importance order assumes that the criterion that is most sensitive to a change in the score is the most important. However, in most cases, the importance or priority order is specified by the user or community interest group. Without the need to assign explicit weights to the selection criteria, the importance order can be rearranged to undertake 'what if' scenarios using the MO-DSS based on stakeholder interests and expert opinion.

Best and worst composite scores for each alternative are determined by solving 2 linear programs. For a total of *m* decision criteria:

Best Composite Score (Worst Composite Score):

$$\text{Maximise (minimise): } \sum_{i=1}^{m} w(i) \times Sc(i,j) \quad (1)$$

$$\text{Subject to: } \sum_{i=1}^{m} w(i) = 1 \quad (2)$$

$$w(1) \geq w(2) \geq ... \geq w(m) \geq 0 \quad (3)$$

where $w(i)$ is weight factor based on the importance order for decision criterion i, and $Sc(i,j)$ is score of alternative j evaluated for decision criterion i.

The best and worst composite scores reflect the most optimistic and pessimistic solutions consistent with the importance order for the criteria used for evaluation, and represent the full range of possible composite scores for the given importance order.

Ranking of alternatives

Computation of the best and worst scores can be used to rank the alternative management systems. By definition, alternative j dominates all other alternatives if the worst score for alternative j is greater than the best scores for all other alternatives. If clear dominance is not established between the alternatives (i.e. partial ranking), then a method to rank the alternatives is needed. One method to select the preferred alternative is to rank, in descending order, the average of the best and worst composite scores for the management systems (Yakowitz *et al.* 1993). The determination of the best and worst composite scores establishes the maximum and minimum overall score possible for any combination of weights consistent with the importance order.

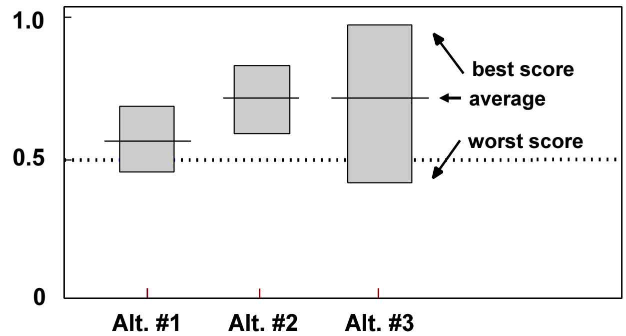

Figure 3. Ranking of current (dotted line) and alternative management systems using the average of the best and worst composite score.

In addition, the difference between the best and worst composite scores is a measure of the sensitivity of the outcome to the weightings of the decision criteria. Figure 3 provides an example of an outcome from the MO-DSS. Here, the average of the best and worst composite score for alternatives (Alt. #1, Alt. #2 and Alt. #3) is better than the current practice (which scores 0.5). Alternatives #2 and #3 have an equal average value, and so both would be preferred to Alternative #1. However, the length of the bars is an indication of the sensitivity of the outcome to the importance order. Consequently, Alternative #2 is

Table 2. Summary of scenarios by importance order

Importance order of criteria	Scenario 1	Scenario 2	Scenario 3
1	All criteria are of equal importance	Responsive	Interpret, Acceptance, Cost
2		Capture	
3		Interpret	
4		Error	Frequency, Error
5		Stable	
6		Frequency	Responsive, Mappable
7		Cost	
8		Aggregate	Capture, Stable, Aggregate
9		Mappable	
10		Acceptance	

preferred to Alternative #3 as the worst composite score for Alternative #2 is better than the current practice, while in some vector weightings in which Alternative #3 is less preferred to the current practice.

Application to evaluate the indicators

Three scenarios were chosen to demonstrate the application of a multiobjective approach to evaluating indicators of sustainability. These were: Scenario 1, a conventional linear function where all criteria are of equal importance; Scenario 2, an ordinal ranking of the criteria in order of importance; Scenario 3, an ordinal ranking but with clustering of importance.

Indicators were identified and given scores following methods outlined in the section Selection Criteria for Sustainability Indicators above. Scores for 10 selection criteria for crop productivity indicators are given in Dalal *et al*. (1998).

Each indicator was evaluated against the criteria using a rating scale of 0–1. The scoring presented in Table 1 was prepared by averaging the group's judgment, however, it would also be possible to ascertain the score matrix based on individual judgment, with weightings associated to reflect the level of expertise of the assessors.

Determining an importance order. An appealing feature of the MO-DSS is the use of an importance order to overcome the contentious issue of assigning numerical weightings to the criteria. Three scenarios where all criteria are equally important, ranking criteria in order of importance and ranking criteria with clustering of importance (Table 2) demonstrate the versatility of the MO-DSS analysis.

In Table 2, Scenario 2 shows an ordinal ranking of the selection criteria, where Responsive is regarded as the most important criterion. In accordance with the importance order, there is more weighting on this indicator than any of the remaining criteria. After Responsive, Capture is the next most important criteria, followed by Interpret, then Error, and so on. For Scenario 2, Acceptance is the least important criteria, and so has the minimum amount of weighting that is consistent with the importance order.

Scenario 3 has 4 clusters of importance. In the first cluster, Interpret, Acceptance and Cost are all of equal importance, but are more important than the second clustering of Frequency and Error. Similarly, these 2 criteria are more important than Responsive and Mappable. For Scenario 3, Capture, Stable and Aggregate are of equal importance, but are judged to be of least importance.

Perspective on importance orders. The MO-DSS is structured to accommodate the range of possible combinations of the importance orders (Yakowitz *et al*. 1993, 1997). From the above example, it can readily be seen that perspective from stakeholders, technical, interests groups, catchment representatives and others can be utilised in the decision making process. Separate scenarios may be developed or grouped, depending on the intent of the application. Importantly, participatory involvement to supply information and determine the importance order of the decision criteria should also improve the acceptance of the outcomes, and hence ownership, thereby increasing the rate of adoption by catchment stakeholders.

Outcomes. The outcomes from the 3 scenarios are presented in Figures 4*a*, 4*b* and 4*c* respectively.

The linear function calculation (Fig. 4*a*) essentially shows the average score for each benchmark indicator. In this example, grain protein has the highest score, and is preferred to the other indicators. In relative terms, there is little difference between the 7 indicators, which may mask other items that need to be considered in the analysis. The calculation, while simple, provides little information on the spread of score values. For example, grain protein, yield and potential yield have a median value of 0.8, making these 3 indicators indistinguishable. In addition, the coefficient of variation for grain yield is 19%, compared with 15% for potential yield and 8% for grain protein.

When a multiobjective approach is used, more information is provided to the decision-makers. Figure 4*b* shows the full range of composite scores consistent with the importance order of the evaluation criteria. On the basis of the average of the best and worst scores, there is little to distinguish between potential yield, WUE, $/WUE, grain protein and grain N. However, for some weighting vectors, the composite scores for potential yield, WUE and $/WUE are better than the best composite score for grain protein. Other factors, therefore, not included in the decision making process may need to be considered before a decision can be made.

Figure 4*c* gives the results from Scenario 3 where a cluster ranking of the importance order is used. These outcomes provide a greater degree of separation between the indicators. The reduced range of composite scores between best and worst is a reflection of decreased sensitivity (and hence improved stability) to the importance order. On the basis of the average of the best and worst composite score, grain yield and grain protein would be the preferred indicator.

Figure 4. Evaluation of indicators using MO-DSS with (*a*) equal importance (Scenario 1), (*b*) ordinal importance (Scenario 2) and (*c*) clustered hierarchical importance (Scenario 3) of selection criteria. Composite scores are shown on the *x*-axis and indicators on the *y*-axis.

In summary, these outcomes demonstrate the use of a multiobjective approach to the evaluation of indicators of sustainability. The structure of the MO-DSS accommodates the inputs from a variety of information sources and judgments from catchment stakeholders, community representatives and the opinions of technical experts. Each of these groups may identify, either individually or by group processes, an importance order for the evaluation criteria. Participation in this way can improve the acceptance of outcomes and increase the rate of implementation. Importantly, the visual representation of the outcomes from the MO-DSS simplifies the interpretation by user groups and individuals. Based on the outcomes, it is possible to define other scenarios and visually compare the results with earlier analyses.

Conclusion

Although sustainability indicators for sustainable farming systems have been identified, they remain largely untested. Widespread use of these indicators would provide an opportunity to test their ability to evaluate best management practices for sustainable farming systems in the grain industry. Continual improvement in selecting these indicators is envisaged through the implementation of environmental management systems such as ISO 14000 series (Standards Australia/Standards New Zealand 1995, 1996), and also other systems which could be used in monitoring the sustainability of the grains industry.

In attempting to relate the sustainability concept to the grains industry, we must consider the overall impact of the grains industry on societal values such as environmental, economic, social and aesthetic aspects, both on-farm and beyond the farm-gate.

Acknowledgments

We thank Land and Water Resources Research and Development Corporation for financial assistance to the Consultancy on Monitoring Sustainability in the Grains Industry: A Central Queensland Pilot Study. This report originated from that study.

We thank the Consultancy Team members, Professor P. Cornish, Dr K. Srivastava, Dr S. Lockie, and Messrs. R. Noble, A. Ross, P. Clarke, V. Cummins, D. Johnston, H. Hunter, C. Carroll and J. Mullins for their contribution to the original report. We also thank Dr G. Bedford and 4 anonymous reviewers for their numerous suggestions.

References

Acton, D. F., and Gregorich, L. J. (1995). 'The Health of Our Soils—Towards Sustainable Agriculture in Canada.' (Centre for Land and Biological Resources Research, Research Branch, Agriculture and Agri-Food Canada: Ottawa.)

Arshad, M. A., Lowery, B., and Grossman, B. (1996). Physical tests for monitoring soil quality. *In* 'Methods for Assessing Soil Quality'. Special Publication No. 49. (Eds J. W. Doran and A. J. Jones.) pp. 123–41. (Soil Science Society of America: Madison.)

Beattie, A. J., Majer, J. D., and Oliver, I. (1993). Rapid biodiversity assessment: a review. *In* 'Rapid Biodiversity Assessment'. pp. 4–14. (Research Unit for Biodiversity and Bioresources, Macquarie University: Sydney.)

Brown, L. R. (1981). 'Building a Sustainable Society.' (Worldwatch Institute: Washington DC.)

Carroll, C., Halpin, M., Burger, P., Bell, K., Sallaway, M. M., and Yule, D. F. (1997). The effect of crop type, crop rotation and tillage practice on runoff and soil loss on a Vertisol in central Queensland. *Australian Journal of Soil Research* **35**, 925–9.

Dalal, R. C., Walker, J., Shaw, R. J., Lawrence, G., Yule, D., Lawrence, P., Doughton, J. A., Bourne, A., Duivenvoorden, L., Choy, S., Moloney, D., Turner, L., King, C., Dale, A., Srivastava, K., Noble, R., Ross, A., Clarke, P., Cummins, V., Johnston, D., Hunter, H., Carroll, C., Lockie, S., and Mullins J. (1998). 'Monitoring Sustainability in the Grains Industry: a Central Queensland Pilot Study.' Consultancy Report to LWRRDC, Canberra. (The State of Queensland, Department of Natural Resources: Brisbane.) 63 pp.

Dumanski, J., and Smyth, A. (1993). The issues and challenges of sustainable land management. International Workshop on Sustainable Land Management for the 21st Century, University of Lethbridge, Alberta, Canada.

FAO (1946). 'Future Global Management.' (FAO: Rome.)

Hamblin, A. (1992). 'Environmental Indicators for Sustainable Agriculture.' (Commonwealth of Australia: Canberra.)

Heal, O. W., Struwe, S., and Kjoller, A. (1996). Diversity of soil biota and ecosystem function. *In* 'Global Change and Terrestrial Ecosystems'. (Eds B. Walker and W. Streffen.) pp. 385–402. (Cambridge University Press: Cambridge.)

Herrmann, T. (1994). 'Right Rotations: Crop Rotation Sustainability Index.' (Primary Industries, South Australia: Adelaide.)

International Union for Conservation of Nature and Natural Resources (1980). 'World Conservation Strategy: Living Resource Conservation for Sustainable Development.' (United Nations: Morges, Switzerland.)

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F., and Schuman, G. E. (1997). Soil quality: a concept, definition and framework for evaluation. *Soil Science Society of America Journal* **61,** 4–10.

Lane, L. J., Ascough, J. C., and Hakonson, T. E. (1991). Multiobjective decision theory—decision support systems with embedded simulation models. *Proceedings of the Irrigation and Drainage IR Division, ASCE*, 445–51.

Lawrence, G., Lyons, K., and Momtaz, S. (1996). ‘Social Change in Rural Australia, RSERC.’ (Central Queensland University: Rockhampton.)

Lawrence, P. A. (1996). The role of data sources and simulation model complexity in using a Prototype Decision Support System. PhD Dissertation, School of Renewable Natural Resources, University of Arizona, Tucson.

Littleboy, M. (1997). Spatial generalisation of biophysical models for quantitative land evaluation: a case study for dryland wheat growing areas of Queensland. PhD Thesis, The University of Queensland, St Lucia.

Pankhurst, C. E. (1997). Understanding soil biodiversity. *Rural Research* **175**, 25–8.

Rendell, R., O’Callaghan, P., and Clarl, N. (1996). ‘Families, Farming and the Future. Fast Project. FM500 and Sustainable Technology.’ (Neil Clark and Associates: Bendigo, Victoria.)

Ridge, P., Bell, A., Medway, J., and Clark, N. (1996). Probing water use efficiency and crop productivity in southern New South Wales, and in the Wimmera and Mallee of Victoria. *In* ‘Families, Farming and the Future’. Fast Project. FM500 and Sustainable Technology. (Neil Clark and Associates: Bendigo: Victoria.)

Shaw, R. J. (1997). The role of models in decision making for natural resource use and management. Workshop Proceedings on The Role of Computer Modelling in the Development and Implementation of Land and Water Management Plans for Integrated Catchments, Melbourne, June 1996. Murray-Darling Basin Commission, Canberra.

Smith, K. (1993). ‘An Economic Study of Queensland Grains Industry.’ (Queensland Department of Primary Industries: Brisbane.)

Standards Australia/Standards New Zealand (1995). AS/NZS ISO 14004. ‘Environmental Management Systems—General Guidelines on Principles, Systems and Supporting Techniques.’ (Standards Australia: Homebush, New South Wales.)

Standards Australia/Standards New Zealand (1996). AS/NZS ISO 14001. ‘Environmental Management Systems—Specifications for Guidance to Use.’ (Standards Australia: Homebush, New South Wales.)

Standing Committee on Agriculture (1991). Sustainable agriculture. Report to Australian Agriculture Council by a Working Group in Sustainable Agriculture. Standing Committee on Agriculture Technical Report Series No. 36. CSIRO, Canberra.

Standing Committee on Agriculture and Resource Management (1998). Sustainable agriculture: assessing Australia’s recent performance. A Report to SCARM of the National Collaborative Project on Indicators for Sustainable Agriculture. SCARM Technical Report 70. CSIRO Publishing, Collingwood, Victoria.

State of the Environment Advisory Council (1996). ‘Australia, State of the Environment 1996.’ (CSIRO Publishing: Collingwood, Vic.)

The Montreal Process (1995). ‘Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests.’ (Canadian Forest Service: Hull, Quebec.)

United Conference on Environment and Development (1993). ‘Agenda 21: Programme of Action for Sustainable Development.’ (United Nations: New York.)

United Nations Conference on the Human Environment (1972). ‘Development and Environment.’ (United Nations: Stockholm, Sweden.)

Walker, J., and Reuter, D. G. (1996). ‘Indicators of Catchment Health: A Technical Perspective.’ (CSIRO Publishing: Collingwood, Vic.)

WCED (World Commission on Environment and Development) (1987). ‘Our Common Future.’ (Oxford University Press: Oxford.)

Wymore, A. W. (1988). ‘Structuring system design decisions. Proceedings. International Conference on Systems Science and Engineering (ICSSE’88).’ (Ed. C. Weimin.) pp. 704–9. (International Academic Publishers: Beijing.)

Yakowitz, D. S., Lane L. J., Stone, J. J., Heilman, P., Reddy, R., and Imam, B. (1992). Evaluating land management effects on water quality using multi-objective analysis within a decision support system. *In* ‘Proceedings of the 1st International Conference on Groundwater Ecology’. pp. 365–73. (Tampa, Florida.)

Yakowitz, D. S., Lane, L. J., and Szidarovszky, F. (1993). Multi-attribute decision making: dominance with respect to an importance order of the attributes. *Applied Mathematics and Computers* **54,** 167–81.

Yakowitz, D. S., and Weltz, M. A. (1997). An algorithm for computing multiple attribute value measurement ranges with application to farm or rangeland management decisions. USDA Agricultural Research Service. *In* ‘Multicriteria Evaluation in Land-use Management: Methodologies and Case Studies’. (Eds E. Beinat and P. Nijkamp.) (Kluwer Publishers: Dorecht, The Netherlands.)

Received 29 July 1998, accepted 21 April 1999