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A Simple Performance-Based Index for Assessing Multiple Agroecosystem Functions

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ABSTRACT

Evaluating the impact agricultural practices have on agroecosystem functions is essential to determine the sustainability of management systems. This paper presents an approach to determine the relative sustainability of agricultural practices. A simple ranking procedure using a relative scoring method is proposed to discriminate among treatments based on the status of crop and soil parameters within different agroecosystem functions. Summing scores across agroecosystem functions allows for the identification of agricultural practices that are performing optimally based on functions included in the procedure. An example, using data from a long-term cropping systems experiment in the western Corn Belt, found the indexing procedure to successfully discern differences in overall performance across four agroecosystem functions between conventional [continuous corn (*Zea mays* L.) cropping sequence at a fertilization rate of 180 kg N ha^{-1}] and alternative {corn–oat (*Avena sativa* L.) + clover (*Trifolium pratense* L.)–grain sorghum [*Sorghum bicolor* (L.) Moench]–soybean [*Glycine max* (L.) Merr.] cropping sequence at a fertilization rate of 90 kg N ha^{-1}} management systems. The simplicity, inclusiveness, and inherent flexibility of the indexing procedure can be considered benefits and drawbacks, depending on the point of view taken. Data requirements of the approach, however, are stringent. Consequently, its most appropriate use may be with data from long-term agroecosystem experiments.

Interest in sustainable agriculture has increased the importance of understanding the impact of management practices on agroecosystem functions. Agroecosystem functions, such as food and fiber production, nutrient cycling, mediation of water flows, and regulation of greenhouse gas fluxes, impact the performance of agricultural management systems by affecting productivity, environmental quality, and human and animal health (Larson and Pierce, 1991; Parr et al., 1992; Doran and Parkin, 1994; Acton and Gregorich, 1995; Daily et al., 1997). Determining the impact of management decisions on the full suite of agroecosystem functions is necessary to determine the sustainability of agricultural production systems.

Approaches to assess agroecosystem functions vary. A common approach is through single indicator–single response studies (Bauer and Black, 1994; Mielke and Schepers, 1986; Voorhees et al., 1989; Cassman et al., 1992; Patriquin et al., 1993; Insam et al., 1991). These studies, while useful in understanding the impact of singular components on an agroecosystem function (e.g., impact of soil organic C on crop yield), do not provide a comprehensive appraisal of agroecosystem performance. Multiple and stepwise regression and principle-component analysis represent other approaches to assess the relative impact of individual indicators on specific agroecosystem functions (Brubaker et al., 1994; Smith et al., 1994; Wander and Bollero, 1999), but they fail to characterize overall performance across multiple functions.

One approach that perhaps comes closest to assessing the impact of management on multiple agroecosystem functions involves the use of performance-based indices (Doran and Parkin, 1994, 1996; Karlen and Stott, 1994). Based on the general method of multiattribute ranking (Stillwell et al., 1981; Edwards and Newman, 1982), values of indicators are scored based on their relative difference from a standard or optimum value. Indicators are categorized into elements within specific agroecosystem functions, and functions are weighted based on their relative importance within the context of climatic, geographical, or socioeconomic conditions. While this approach suffers from shortcomings of being inherently retrospective and overly simplified with respect to quan-

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tifying functional relationships among agroecosystem components (Wagenet and Huston, 1997), it has been demonstrated to be particularly useful in discriminating among a diverse array of management systems in the USA and abroad (Karlen et al., 1994; Ericksen and McSweeney, 1999; Karlen et al., 1999; Glover et al., 2000).

There is a need to further develop indexing approaches to determine the relative sustainability of agricultural management systems within the context of multiple agroecosystem functions. The objective of this paper is to present one such approach.

METHODS

Efforts to develop a performance-based index to evaluate the relative sustainability of agricultural management systems arose from analyzing and evaluating data from a long-term cropping systems experiment in the western Corn Belt. The experiment, initiated in 1983, is being conducted on the Nebraska Agricultural Research and Development Center near Mead, NE, on a Sharpsburg silty clay loam (fine, montmorillonitic mesic Typic Agriudoll). The experiment is comprised of seven cropping systems (three monocultures, two 2-yr rotations, and two 4-yr rotations) with three rates of N fertilizer. Each phase of every rotation occurs every year. Treatment combinations are replicated five times. Yield and yield components are assessed annually while soil parameters are measured every 2 or 4 yr, depending on the parameter. A more thorough review of the treatments and data set are presented elsewhere (Peterson and Varvel, 1989a, 1989b, 1989c; Varvel, 1994).

For this paper, a restricted set of treatments from the experiment was used in an example of the indexing procedure. Specifically, results from conventional (continuous corn cropping sequence at a fertilization rate of 180 kg N ha^{-1}) and alternative (corn–oat + clover–grain sorghum–soybean cropping sequence at a fertilization rate of 90 kg N ha^{-1}) treatments will be presented.

The indexing procedure followed four basic steps: data grouping, calculation of averages, ranking and scoring treatments, and summing of scores within and across agroecosystem functions.

Step 1: Group Data within Agroecosystem Functions

The procedure is initiated by surveying the data set for indicators that could be grouped within agroecosystem functions. Categorization and grouping of indicators can follow general guidelines presented by Costanza et al. (1997) where 17 ecosystem functions were presented in the context of assigning economic value to each. Of the 17 functions presented by Costanza et al., seven have direct applicability to agroecosystems: food production, raw materials production, nutrient cycling, erosion control, greenhouse gas regulation, water regulation, and waste treatment (Table 1). Agroecosystem performance following these guidelines could be presented in the following manner:

$$\text{Agroecosystem performance} = f\,(\text{food production, raw materials production, nutrient cycling, erosion control, greenhouse gas regulation, water regulation, waste treatment}) \quad [1]$$

Within each agroecosystem function, indicators are selected to characterize the performance of that function. Examples vary and depend on the scope and detail of the data set used. For instance, indicators of food production might include data on grain yield, percentage of nutrients in grain, or storage and handling parameters. Indicators of greenhouse gas regulation may include CO_2 and CH_4 flux, N_2O emissions, and selected soil properties such as soil organic C and near-surface soil NO_3.

It is unlikely that all functions can be included when determining agroecosystem performance with this procedure. For instance, when using an existing data set, as with our example, only four agroecosystem functions could be represented with appropriate indicators. Functions with associated indicators included food production (grain yield and grain N content), raw materials production (stover yield and stover N content), nutrient cycling (residual or postharvest soil NO_3 at 0–183 cm and soil pH at 0–7.6 cm), and greenhouse gas regulation (soil organic C at 0–30.5 cm and early spring soil NO_3 at 0–7.6 cm). If presented as equations, agroecosystem functions using the example data set would be characterized in the following manner:

$$\text{Food production} = f\,(\text{grain yield, grain N content}) \quad [2]$$

$$\text{Raw materials production} = f\,(\text{stover yield, stover N content}) \quad [3]$$

$$\text{Nutrient cycling} = f\,(\text{residual soil } NO_3\text{, soil pH}) \quad [4]$$

$$\text{Greenhouse gas regulation} = f\,(\text{soil organic C, early spring soil } NO_3) \quad [5]$$

Once indicators have been selected to represent agroecosystem functions, the relative importance of each function on agricultural sustainability is estimated. While this is an inherently subjective task, regional differences in emphasis on production and local and/or global environmental quality may require some functions to receive greater weight than others. Weighting values range from 0 to 1, and the sum of the weights does not exceed 1. To simplify the presentation of the example provided here, equal weight was given to each agroecosystem function:

Table 1. Agroecosystem functions with potential indicators (subset of functions taken from Costanza et al., 1997).

Agroecosystem function	Potential indicators
Food production	Yield
	Quality and nutrition of food produced
Raw materials production	Yield
	Quality and nutrition of fiber produced
Nutrient cycling	Nutrient cycling time scale
	Macronutrients and micronutrients
	Soil organic matter
	Microbial biomass
	Soil pH
	Number of trophic levels
Erosion control	Erosion rate
	Sediment load
	Textural change
	Percent residue and live plant cover
	Aggregate stability
	Glomalin
Greenhouse gas regulation	CO_2, CH_4, N_2O flux
	Soil C sequestration rate
Water regulation	Surface soil physical condition
	Soil hydraulic properties
Waste treatment	Heavy metals
	Levels of excess nutrients
	Residence times of chemicals
	Presence or absence of pathogenic organisms
	Microbial indicators of detoxification potential

$$\text{Agroecosystem performance} = f\,[(\text{food production} \times W_{fp}),\ (\text{raw materials production} \times W_{rmp}),\ (\text{nutrient cycling} \times W_{nc}),\ (\text{greenhouse gas regulation} \times W_{ggr})] \quad [6]$$

where W_{fp}, W_{rmp}, W_{nc}, and W_{ggr} are the relative weights given to food production, raw materials production, nutrient cycling, and greenhouse gas regulation, respectively (all 0.25). Using this approach creates unintended weighting of each function proportional to the number of indicators associated with it (i.e., functions characterized by a greater number of indicators have a greater impact on agroecosystem performance). Consequently, the relative weights may be adjusted for each function to account for differences in the number of indicators among functions.

Step 2: Calculate Treatment Averages

With indicators categorized within agroecosystem functions, the next step is to calculate treatment averages for each indicator. The type of average calculated depends on characteristics of the indicator. For example, some indicators are best evaluated over time; doing so lessens the influence of climatic variation (e.g., crop yield year to year). Conversely, some indicators are cumulative in their influence on agroecosystem functions, increasing or decreasing over time (e.g., soil organic C).

For the data set used in the development of the procedure, treatment averages were calculated over time (12 yr) for all indicators except soil organic C and soil pH, which were both calculated at the end of a 12-yr period (Table 2).

Step 3: Rank and Score Treatments

Treatment values are ranked for each indicator in ascending or descending order, depending on whether a higher value for the indicator is considered good or bad with respect to enhancing agricultural sustainability. Ranking can also follow guidelines other than simple *good or bad* criteria. For instance, where an ecological threshold is known for an indicator [e.g., integrated pest management (IPM) thresholds for pest presence or soil pH for selected microbiological processes], treatments can be ranked according to their distance from a threshold value.

Table 2. Conventional and alternative treatment averages for indicators used to represent agroecosystem functions.

Agroecosystem function/indicators	Treatment† Conventional	Alternative
Food production/		
Grain yield, kg ha^{-1}	7077‡b*	8086a
Grain N content, g kg^{-1}	14.3a	13.6b
Raw materials production/		
Stover yield, kg ha^{-1}	6841b	7703a
Stover N content, g kg^{-1}	8.7a	6.6b
Nutrient cycling/		
Residual soil NO_3–N, 0–183 cm, kg ha^{-1}	133a	39b
Soil pH, 0–7.6 cm	5.40b	5.95a
Greenhouse gas regulation/		
Soil organic C, 0–30.5 cm, kg ha^{-1}	50 914	55 979
Early spring soil NO_3–N, 0–7.6 cm, kg ha^{-1}	13a	8b

* Values within a row for an indicator followed by a different letter are significantly different at $P \leq 0.05$ using Fisher's protected LSD.

† Conventional treatment, continuous corn cropping sequence at a fertilization rate of 180 kg N ha^{-1}; alternative treatment, corn–oat + clover–grain sorghum–soybean cropping sequence at a fertilization rate of 90 kg N ha^{-1}.

‡ Averages for grain and stover yield, grain and stover N content, and soil NO_3 were calculated over a 12-yr period (1983–1994). Averages for soil organic C and soil pH were determined from 1994 data only. Data for grain and stover yield and N content in the alternative treatment are specific for corn.

This step requires that assumptions be made before ranking treatments with respect to an individual indicator's impact on an agroecosystem function. For the example data set, the following assumptions were made for the food production, raw materials production, nutrient cycling, and greenhouse gas regulation functions, respectively: (i) higher values for grain yield and N content were considered to enhance agricultural sustainability; (ii) higher stover yield and N content were considered to do the same; (iii) lower levels of residual soil NO_3 were considered to reflect more efficient nutrient uptake by crops, and a value of 7.0 for soil pH was established as an optimum for nutrient cycling based on knowledge of row crop performance in the western Corn Belt as well as pH-dependent biological processes related to nutrient cycling efficiency (Patriquin et al., 1993; Smith and Doran, 1996); and (iv) higher values for soil organic C represented reduced loss of soil C to the atmosphere while lower levels of early spring soil NO_3 represented decreased potential for N_2O emissions from denitrification.

After the treatment values are ranked, they are scored based on their relative difference from the optimal value. The most straightforward approach for data arranged in descending order is to assign a score of 1.0 to the highest treatment. Remaining treatment values would then be scored based on their percentage of the highest treatment value. For example, if Treatment A has the highest grain yield among three treatments at 4.0 Mg ha^{-1}, followed by Treatment B and C at 3.0 and 2.0 Mg ha^{-1}, then based on an assumption that higher grain yield enhances the food production function and thereby agricultural sustainability, Treatment A, B, and C would be assigned scores of 1.0, 0.75 (3.0/4.0), and 0.50 (2.0/4.0).

Whereas the highest treatment values are in the denominator when treatments are arranged in descending order, treatments arranged in ascending order (where a lower value is more optimal) are scored with the lowest value in the numerator. Additionally, for indicators that possess a threshold value, treatments are scored with the value in either the numerator or denominator depending on whether treatment values are above or below that value. Treatment rankings and scores for the example data set are presented in Table 3.

When using this scoring approach, comparisons are internalized for data with an unknown threshold value. While this may be considered a drawback, in many cases the highest or lowest value for an indicator is not known; technological breakthroughs and improvements in management change indicator thresholds regularly. This makes the use of an internalized, relative scoring approach appropriate for some indicators.

Furthermore, this indexing procedure assumes the performance of an agroecosystem function decreases linearly from an optimal state. This feature is likely wrong for most indicators. However, depending on an indicator's impact on an agroecosystem function, changes in performance could be expressed using an appropriate mathematical relationship (e.g., logarithmic or exponential), and scores could be computed from a prediction curve (Karlen et al., 1994, 1999).

Step 4: Sum Scores within and across Agroecosystem Functions

The relative performance of one treatment to another within an agroecosystem function is determined by summing

Table 3. Rank and scores of conventional and alternative treatments for indicators within agroecosystem functions.

Rank	Treatment	Score	Rank	Treatment	Score
		Food production			
	Grain yield†			Grain N content	
1	Alternative	1.00	1	Conventional	1.00
2	Conventional	0.88	2	Alternative	0.95
		Raw materials production			
	Stover yield			Stover N content	
1	Alternative	1.00	1	Conventional	1.00
2	Conventional	0.89	2	Alternative	0.76
		Nutrient cycling			
	Residual soil NO_3‡			Soil pH§	
1	Alternative	1.00	1	Alternative	0.85
2	Conventional	0.29	2	Conventional	0.77
		Greenhouse gas regulation			
	Soil organic C			Early spring soil NO_3	
1	Alternative	1.00	1	Alternative	1.00
2	Conventional	0.91	2	Conventional	0.62

† Data for grain yield and N content, stover yield and N content, and soil organic C ranked in descending order with the highest value given a score of 1.0. Lower values were scored by division with the highest value.
‡ Data for soil NO_3 ranked in ascending order with the lowest value given a score of 1.0. Higher values were scored by dividing the lowest value by each higher value.
§ Soil pH scored using a threshold value of 7.0, dividing each lower value by the threshold, and dividing the threshold by each higher value.

indicator scores within functions. If indicators possess equal importance with regard to their impact on a particular function (as assumed in the example), then summing across indicators can proceed without giving one indicator greater priority over others.

If, however, one indicator has an overriding effect on an agroecosystem function, its precedence over others can be expressed by giving it greater numerical weight. One approach to achieve this is to give the indicator with the overriding effect, hereafter referred to as the benchmark indicator, full weight when summing across indicators within a function while giving nonbenchmark indicators less numerical weight based on the strength of their association to the benchmark indicator. A weighted score for each nonbenchmark indicator could be derived by multiplying each nonbenchmark indicator score with the correlation coefficient (r) from the regression between treatment values for benchmark and nonbenchmark indicators. Weighted scores for each nonbenchmark indicator would then be added to the score of the benchmark indicator within an agroecosystem function. In the event that the correlation between a benchmark and nonbenchmark indicator is negative, the absolute value of r must be used for the summation process to work.

Upon summing scores within agroecosystem functions, the remaining step is to sum scores across functions. The final score would reflect a relative ranking of agroecosystem performance among treatments for functions included in the procedure. If desired, scores can be scaled to 100 to express them in a more familiar context (Table 4).

RESULTS AND DISCUSSION

Results from Example

The indexing procedure was effective at discriminating between alternative and conventional treatments within and across agroecosystem functions. As shown in Table 4, the overall agroecosystem performance score of the alternative treatment was 15 points higher than the conventional treatment when scores were scaled to 100. Much of the disparity between treatments was driven by substantial differences in function scores for nutrient cycling and greenhouse gas regulation. The alternative treatment had significantly lower levels of residual and early spring soil NO_3, significantly higher soil pH, and moderately higher levels of soil organic C (5065 kg ha^{-1}) compared with the conventional treatment.

The capacity of the indexing procedure to translate significant as well as moderate relative differences in indicators between treatments into differences in an overall index score is important. It indicates the procedure was useful in discerning the overall performance of the contrasting cropping systems across multiple agroecosystem functions. While stand-alone assessments of individual indicators within an agroecosystem function will continue to be useful measures of agroecosystem performance, this indexing procedure provides users with the ability to evaluate management systems in a broader context.

Benefits and Drawbacks

The approach to assess agroecosystem performance outlined in this paper is simple and conceptually straightforward. It is inclusive as far as assessing the performance of agricultural management systems; it includes as many agroecosystem functions in the calculation procedure as there are data available. Furthermore, opportunities to assign greater or lesser importance to an agroecosystem function or individual indicator is possible with this procedure. Weighting agroecosystem functions and assigning benchmark indicators allows users to adapt the procedure to reflect a diversity of climatic, geographical, or socioeconomic conditions.

While the simplicity, inclusive nature, and inherent flexibility of the indexing approach is appealing, these factors can also be considered drawbacks. Indexing approaches such as this can fall short in accurately representing the complexity of the agroecosystems they aim to characterize. Agroecosystems, by their very nature, are highly complex systems, whose discrete parts and interactions are difficult to quantify. Therefore, the same reasons that make indexing attractive also limit

Table 4. Agroecosystem performance scores for conventional and alternative treatments.

	Agroecosystem function				Agroecosystem performance scores	
Treatment	Food production	Raw materials production	Nutrient cycling	Greenhouse gas regulation	Not scaled	Scaled to 100
Conventional	1.88	1.89	1.06	1.53	6.36	79.5†
Alternative	1.95	1.76	1.85	2.00	7.56	94.5

† Scores scaled to 100 using a maximum nonscaled score of 8.00.

its use to general characterizations of agroecosystem performance.

A major concern with the index relates to its emphasis on the environmental dimension of agricultural sustainability. The index, due to its focus on agroecosystem functions, possesses a strong environmental bias based on the types of indicators used to quantify performance. Agricultural sustainability, however, encompasses not just an environmental dimension, but economic and social dimensions as well (Harwood, 1990). An ideal index would integrate all three dimensions. Failure to do so would result in a slanted representation of agroecosystem performance and agricultural sustainability.

For example, nowhere with the approach outlined above would the user know the conventional treatment had an average net return \$56.41 ha^{-1} yr^{-1} greater than the alternative treatment (Glenn Helmers, personal communication, 2000). Nor would the user be aware of the social consequences of either treatment (e.g., attributes of producer satisfaction, labor requirements, output/input energy ratio, and off-site costs of environmental degradation). These are major omissions when evaluating agroecosystem performance. However, integrating environmental, economic, and social dimensions in a single index is a daunting task, owing to the complexity of each dimension (Sands and Podmore, 2000). A more practical approach to quantify agroecosystem performance and agricultural sustainability would be to start with a single dimension—as essentially done here—and then work toward an integrated measure.

A more specific drawback of the indexing approach relates to the difficulty in determining which agroecosystem function (or functions) directs an overall performance score upward or downward. The inclusion of many agroecosystem functions in the procedure requires performance scores to be dissected to determine each function's relative impact on the final score. This task may seem cumbersome, but it forces users to develop a better understanding of individual management decisions with respect to their impact on components of agricultural sustainability.

The use of numerical weights to assign greater or lesser importance to agroecosystem functions as well as the selection of benchmark indicators may be considered arbitrary because assumptions are needed in each circumstance. Assumptions must be made using best professional judgment based on credible information. Even so, arguments over why one function was given greater weight than another or why one indicator was considered a benchmark indicator and another was not are reasonable, if not expected. Such discourse can be minimized (or at least channeled) by stating assumptions on how data is to be handled before inclusion in the index.

Requirements

Requirements of the indexing procedure are stringent. The fact that the procedure was developed using data from a long-term cropping systems experiment was instrumental in its development. There were numerous characteristics that made the experiment an appropriate data source for the development of an index.

The experiment was conducted over a long enough time period (16 yr) so that treatments could express their impacts on crops, soils, and the environment. Furthermore, treatments in the experiment covered a relatively wide spectrum of management options that included crops (four plus a cover crop), crop sequences (seven), and fertilization levels (three). Consequently, the range of management options increased the likelihood that treatment differences would be found over time.

Additionally, the quantity and quality of data collected during the experiment facilitated the development of the index. Indicators measured throughout the course of the experiment were reflective of a wide range of agroecosystem functions. This is important because the usefulness of agroecosystem performance scores as a relative measure of agricultural sustainability is directly proportional to the number of functions and relevant indicators included in the procedure.

Data requirements of the index, however, do not necessarily limit its use with the type of experiment outlined above. Data from experiments conducted over a shorter time frame (3–5 yr) could be used, depending on the choice of indicators used to represent individual functions. Conversely, data from single point-in-time evaluations (i.e., fenceline comparisons of different management practices) may not be suitable for the index because many agroecosystem functions are best characterized over multiple years.

SUMMARY

A simple performance-based index was developed to determine the relative sustainability of agricultural management systems within the context of multiple agroecosystem functions. The index was successful in discerning differences in agroecosystem performance between contrasting management systems in a long-term cropping systems experiment in the western Corn Belt. Requirements of the indexing procedure, however, may make its use to be most appropriate with data from long-term agroecosystem experiments. Despite this limitation, the procedure has the potential to effectively evaluate management systems across multiple agroecosystem functions, thereby giving users a simple measure to assess agricultural sustainability.

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