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Biophysical indicators of sustainability of North Island hill pasture systems

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Abstract

"Sustainability" is a social construct, and is difficult to define in precise value-free terms. It has ecological (biophysical) and socio-economic dimensions. Biophysical indicators are tools that can be used to define resource status. They cannot directly measure sustainability, but are useful for comparing present resource status with defined limits set within a socio-economic framework. We measured vegetation and soil variables in 4 areas of grazed North Island hill country with different management (fertiliser application/stocking rate) histories (1973 to 1994) and sub-divided into 36 paddocks. Nineteen vegetation (including herbage production); soil chemical, physical and biological; and soil water variables were selected as potentially useful biophysical indicators. Analysis of the results for these variables suggested that pasture botanical composition (especially content of high-fertility responsive grasses and of herbaceous weed species) and earthworm mass/unit area explained most of the variance of the data matrix. These variables were also highly correlated with herbage production, an indicator of likely economic performance. Development of the most suitable indicators requires good understanding of agro-ecosystem function, and is hampered by our lack of understanding of critical processes.

Keywords: biophysical indicators, hill country, pasture, soil, sustainability

Introduction

The sustainability of present agricultural land-use practices is receiving increased public attention, because of increased ecological awareness stimulated in part by the 1991 Resource Management Act (RMA).

"Sustainability" is a social construct, and is difficult to define in precise value-free terms (Pretty 1994). It is generally accepted that sustainable land use has both ecological (or "biophysical") and socio-economic dimensions. Although ecologically sustainable management practices might conflict with short-term economic sustainability, long-term economic performance must be related to conservation of the resource base (Ikerd 1990). However, because we each have unique beliefs there is no single "correct" understanding of sustainability (Pretty 1994), e.g., Wilson (1988) recognised alternative definitions ranging between *ecocentric* (an ecosystem has an intrinsic value, and a capacity which dictates the limits for human activity) and *anthropocentric* (ecosystems should be used to maximise human welfare, and have no value independent of humans). As well as requiring a socio-economic frame of reference, sustainability is meaningless unless spatial and temporal scales are defined (Lefroy & Hobbs 1992).

The RMA aims to promote sustainable management of resources; however, since it does not provide the detail required for implementation, suitable criteria need to be developed (Basher et *al.* 1992). Biophysical indicators are tools that can be used to define resource (e.g., soil, water, vegetation) status. These indicators cannot directly measure sustainability, rather they can be used to compare present resource status with defined limits which fit the current prescription for sustainable practices having acceptable socio-economic outcomes.

The ability to predict long-term resource trends from one-off indicator measurements is limited. Predictability will be increased where measurements are taken over time, or where well-defined land-use patterns have occurred in the past and present-day indicator measurements give an idea of impact on resource status over time, e.g., Lambert *et al. (1984).*

Farmers routinely use a range of biophysical indicators, e.g., soil nutrient status, animal liveweight, pasture cover, primarily to assist in optimising economic performance. Mackay *et* al. (1993) suggested that farmers could extend the range of measurements they make to include indicators which estimate the environmental consequences of farming systems.

Good biophysical indicators should be simple, cheap, obvious and responsive to environmental stresses (Springett 1993). It would also be advantageous if indicators of sustainability of pastoral farming reflected productivity level as well as resource status, given that productivity is an important element of economic performance. Herbage production (quantity and quality) is a useful indicator of both economic performance and resource status. On one hand it drives the economic farm output (animal production), and on the other it reflects aspects of resource status, e.g., vegetation change due to weed ingress or environmental stress, and "health" of the soil resource because it integrates effects of soil fertility, biological activity, physical condition, moisture holding capacity and erosion. For this reason considerable emphasis is given here to identifying variables which reflect herbage production, as well as resource status in an ecological sense.

In this paper we report preliminary analyses of results of measurements of 19 variables or potential "on-site" biophysical indicators made in hill country pastoral systems with four different management histories.

Experimental

Experimental Site

Four 7-ha farmlets at AgResearch's Hill Country Research Station, Ballantrae, near Woodville, were further subdivided into 36 paddocks which varied in aspect and slope within farmlet. Two of the farmlets had high (H) and 2 had low fertiliser (L) application during 1975 to 1980; and little fertiliser had been applied before 1973. One L (LN) and one H (HN) farmlet had fertiliser applications discontinued after 1980, and annual applications of 125 (LL) and 375 (HH) kg/ha superphosphate were continued for the other two. From 1973 to 1993 total applied superphosphate equivalent was 1250, 4625, 4000, and 8875 kg/ha for LN, LL, HN and HH respectively. Agricultural lime was applied to H farmlets in 1975 and 1979, a total of 3750 kg/ha.

Farmlets were set-stocked with breeding ewes, and the initial (1974) stocking rate (SR) of 6.0 ewes/ha was adjusted as herbage production responded to fertiliser treatments (Lambert et al. 1990). Average SR during 1975 to 1993 was 8.3, 10.3, 13.8, and 14.8 for LN, LL, HN, and HH respectively. During the experimental period (October 1993 to December 1994), all paddocks were continuously grazed with sheep on a put-and-take basis, to maintain above-ground pasture biomass at <2500 kg DM/ha. The experimental area was at 250-350 m altitude, and average annual rainfall was about 1200 mm. Soils were yellow-brown earths and related steepland soils, formed from tertiary sediments and sedimentary drift material. Pasture botanical composition varied according to management history, the dominant functional groups being high-fertility responsive grasses (e.g., ryegrass, Yorkshire fog, *Poa trivialis*), low-fertility tolerant grasses (e.g., browntop, sweet vernal, crested dogstail), legumes (e.g., white clover, suckling clover, *Lotus pedunculatus*), weeds (e.g., cat's ear, hawkbit, ribgrass) and moss.

Measurements

Soil, water and vegetation variables were measured in the 36 paddocks during 1993194, and a sub-set of these, chosen to include chemical, physical and biological variables, was selected for analysis and presentation here. Measurements within paddocks were made on microsites with slopes approximating each paddock's average slope (between 7" and 33"). Variables selected were as follows (standard analytical techniques used unless specified):

1. **Soil chemistry** (O-75 mm samples taken in September *1993). Olsen P, total S, exchangeable Ca/Mg ratio.*
2. **Soil organic status** (O-75 mm samples taken in September 1993). *Total organic matter; light organic matter* (density method); *mineral* N (after laboratory incubation of moistened air-dry soil).
3. **Soil biology** *N fixation* (average of four field-based acetylene reduction assays in December 1993, April, June and December *1994); earthworm mass* (fresh weight of the three major species after hand-sorting of O-150 mm depth samples taken in July 1994); *enrthworm species* (number of species encountered during hand-sorting).
4. **Vegetation characteristics** *Herbage production* (annual herbage digestible organic matter production, calculated from total herbage production measured using a grazing exclosure trim technique involving seven harvest periods spanning October 1993 to October 1994, and from digestible organic matter estimates [NIR] on herbage subsamples taken at each harvest); *high fertility responsive (HFR) grass content* (average percentage contribution of HFR grass species to the green component of subsamples as above, but for three of the seven harvests only [November 1993, June and October 1994]); *other species content* (herbaceous weed content, estimated as for HFR grass content); *legume production* (as for HFR grass content, but multiplied by the relevant total DM values); *root surface area* (calculated from root length [optical scanner] and diameter [light microscope] measurements made on roots washed from O-300 mm soil samples taken in August 1994).
5. **Soil physical** (laboratory measurements on O-75 mm samples taken September to November 1994). *Air permeability* (at 200 mm tension); *water conductivity* (unsaturated hydraulic conductivity at 100 mm tension); *porosity* (calculated at 500 mm tension).
6. **Soil water** *Moisture content* (average of weekly TDR measurements to 300 mm depth, for January to April 1994); *runoff* (calculated from a mass

balance model for November 1993 to November 1994, inputs being weather and soil moisture).

Data analysis

Results were consolidated to a data matrix of 36 paddocks by 19 variables. Effect of management treatment (fertiliser/stocking rate regime) on the selected variables was tested by analysis of covariance, treating aspect and slope as covariates and estimating mean values for each variable for four treatment levels (farmlets).

Relationships among variables were assessed by several techniques, including simple correlation; partial correlation with the management treatment effects removed; factor analysis to reduce the number of variables to fewer "factors" of "like" variables (herbage production was not included in factor analysis, but was subsequently correlated with the factors selected); and multiple regression to identify the variables which best accounted for variation in herbage production.

Results

Management treatment influenced herbage production, soil Olsen P, soil mineral N, exchangeable Ca:Mg ratio, N fixation, legume production, HFR grass content, and earthworm mass in a similar fashion, values for these 'variables being highest for HH and lowest for LN (Table 1). The converse pattern applied for other species content and root surface area. Soil total S was higher for HH than the other three farmlets and soil water conductivity was greater on L than H treatments. Soil organic matter was highest for HH.

The first four factors from factor analysis accounted cumulatively for 90% of the sample variance within the data matrix (Table 2). Factor 1, and its most influential component variables (Table 2) had highly significant simple correlations with herbage production (Tables 2, 3). With the exception of HFR grass content and soil mineral N, correlations of the variables in this factor with herbage production were greatly reduced or non-significant when management treatment effects were removed from the analysis using partial correlation (Table 3). Factor 2 and its variables (Table 2) were weakly or not associated with herbage production (Tables 2, 3). Factor 3 and its major contributing variables were moderately or strongly correlated with herbage production (Tables 2, 3). The relationship persisted in the partial correlations for HFR grass content and earthworm mass (Table 3). Factor 4 and its variables (Table 2) were highly correlated with herbage production, the correlations with HFR grasses and earthworm mass remaining strong after removal of management treatment effects (Tables 2, 3).

Multiple regression of the 18 variables against herbage production as the dependent variable, identified four major variables: earthworm mass, HFR grass content, legume production, and other species content. This model explained 89% of the variation in herbage production across the 36 paddocks.

Discussion

Thirteen of the 19 variables selected (i.e., the variables in Table 2 plus herbage production) made significant contributions to the variance within the data set. Soil

Table 1 Mean values for variables across management treatment levels, and significance of differences.

Variables	Units	LN	LL	HN	HH	Signif.
herbage production	t DOM/ha/yr	4.4	6.5	6.6	9.2	
soil Olsen P	mglkg dry soil	6.3	9.3	8.9	33.2	
soil total S	mglkg dry soil	366	388	349	511	***
soil mineral N	mglkg dry soil	236	248	256	324	
exchangeable Ca/Mg ratio		3.0	3.6	4.5	5.5	***
soil organic matter	g/l 00g dry soil	6.6	8.5	8.3	10.1	†
light organic matter	mglkg dry soil	616	568	623	595	ns
N fixation	kg N/ha/day	0.03	0.08	0.05	0.13	
legume production	kg DM/ka	130	271	183	390	***
HF responsive grasses	% by weight	6.7	16.3	25.0	37.3	
other species	% by weight	11.5	7.5	7.6	4.7	**
root surface area	m^2/m^3	70.6	57.3	44.5	34.2	**
earthworm mass	g/m^2	79	101	138	176	
earthworm species	number	3.2	3.9	3.5	3.3	ns
soil air permeability	m/s	2.37	5.18	5.14	4.63	ns
soil macroporosity	% by volume	17.7	16.2	16.4	16.7	ns
soil water conductivity	mm/hour	30.6	27.4	14.7	13.7	
soil moisture content	volumetric %	31.1	28.8	27.1	26.7	ns
runoff	mm/yr	700	748	695	678	ns

Table 2 Proportion of the total sample variance within the matrix explained by the first 4 factors (fitted sequentially), simple correlation of herbage production with the first 4 factors, and simple correlation of the most influential variables from factor analysis with the 4 factors.

	Factor 1		Factor 2		Factor 3		Factor 4	
Proportion of variance explained	0.555		0.198		0.097		0.054	
Correlation with herbage production	0.71	***	-0.12	ns	-0.52	**	0.88	***
Influential variables in factors:								
soil Olsen P	0.95	***					0.60	***
soil total S	0.72	***		***				
soil mineral N	0.65	***						
exchangeable soil Ca:Mg ratio	0.79	***						
N fixation	0.88	***						
legume production	0.61	***						
HF responsive grass	0.74	***		***	-0.63	***	0.84	***
other species							-0.86	***
earthworm mass					-0.64	***	0.68	***
soil water conductivity			–		0.94	***		
soil moisture content			0.85	***				
runoff			0.85	***				

total S and Ca:Mg ratio, N fixation, legume production and soil water conductivity were all strongly linked to the fertiliser/stocking rate treatments imposed, and their usefulness as indicators of resource status was minor when treatment effects were removed. Soil moisture content and runoff were not related to herbage production, so would also have limited value as indicators. Olsen P, which is one of the soil indicators used most widely by farmers, was strongly linked to herbage production, both in its own right and through its presence in Factors 1 and 4. However, it contributed little to explanation of herbage production in regression analysis involving all variables. It was only when both HFR grass and earthworm mass were excluded as independent variables, that Olsen P became the variable selected first. This implied that HFR grass content, earthworm mass and Olsen P were related to herbage production in a similar fashion, but the former two more highly than the latter. Other species content appeared in the regression analysis as a significant variable in explaining differences in herbage production, and was also associated with herbage production when treatment effects were both present and absent in correlation analyses.

These results have obvious constraints. The analytical techniques used assumed linear relationships among variables. This was not always an accurate reflection of the biological relationships, e.g., for herbage production versus Olsen P, Ca:Mg ratio, N fixation, earthworm species, and other species content. Also, had non-linear methods been employed or had a different array of variables been selected, the conclusions reached may have been different.

A problem we encountered in the selection/ interpretation processes, and indeed in designing our measurement programme, was the lack of knowledge regarding ecological processes and interactions among components of our systems, e.g., with regard to soil decomposer activity, soil organic pools, and soil physical characteristics. This problem was also noted by Basher *et al.* (1992). Better knowledge would enhance our ability to select indicators with regard to critical processes affecting ecosystem function.

The four systems considered here were located within one edaphic/climatic zone and the conclusions reached may not be applicable to other zones. Also, the management treatments imposed were not *extreme* perturbations, and hence rapid shifts in system function, which may occur as a result of discontinuous ecosystem change (e.g., Westoby *et al.* 1989) were unlikely to occur.

Bearing in mind the constraints inherent in the analytical approach used, it was interesting that HFR grass content, other species content and earthworm mass were variables which explained a significant proportion of the sample variance in the data matrix, and were well correlated with herbage production both in the presence and absence of treatment effects. As indicators of resource status, all are simple and cheap to measure, they are obvious, and responsive to management practices. Botanical composition is strongly influenced by farm management practices, and reflects underlying soil nutrient and moisture availability. Earthworm mass is an indicator of soil "health" including decomposer activity and physical conditions. These indicators could be expected to reflect historical trends.

Soil organic matter content was not well related to herbage production, and differences across treatments were historical rather than induced by the treatments themselves (unpubl. data). The soil physical and

Table 3 Simple (bottom and left) and partial, [i.e., with management treatment effects removed] (top and right) correlations for herbage production and 18 variables, and simple correlations of each of the most influential variables from Factor Analysis with the first 4 factors (bottom and left).

Variables		HP	OP	TS	MN	Ca:Mg	SOM	LOM	NFix	Leg	HFG	Ospp	Root	Worm	WSpp	AP	Por	WC	SM	RO
herbage production	(HP)		0.32 t	–	0.39 *	–	–	–			0.77 •	-0.38 •		0.56 ***					-0.31 t	
soil Olsen P	(OP)	0.70 ***		–	–	–	–	–	0.53 **		0.34 t									
soil total S	(TS)	0.32 t	0.57 ***		0.48 **	–	0.41 *	–	0.36 •	-0.37 *	0.31 t		-0.44 •				-0.39 *		0.53	0.50 •
soil mineral N	(MN)	0.56 ***	0.51 **	0.58 • *			0.51 **	–	0.37 *	-0.41 *	0.57 ***					-0.32 t	-0.43 •		0.40 *	0.54
exchangeable Ca/Mg ratio	(Ca:Mg)	0.55 ***	0.75 •	0.37	0.33 †		–	–				0.43 •					-0.40 *			
soil organic matter	(SOM)	–	0.40 *	0.54 ***	0.59 ***	–		[illegible]											0.48 •	0.57 ***
light organic matter	(LOM)	–		–	–		–		–	–					-0.40 •			0.46		
N fixation	(NFix)	0.64 ***	0.63 ***	0.57 ***	0.56 [illegible]	0.66 ***	0.35 *	–		–	0.30 t						-0.46 *			
legume production	(Leg)	0.62 ***	0.68 •	–	–	0.63 ***	–	–	0.62 ***				0.31 t			0.44 •	0.29 t		-0.51 **	-0.49 **
HF responsive grass	(HFG)	0.68	0.65 •	0.42 **	0.67 ***	0.57 ***	0.31 t	–	0.61 ***	0.43 •			-0.33 t	0.43 *			-0.40 •			0.45 **
other species	(OSpp)	-0.67 ***	-0.52 •	–	-0.31 t	-0.31 t	–	–	-0.41 *	-0.42 *	-0.56 •		–							
root surface area	(Root)	-0.34 *	[illegible]	-0.45 •	-0.35 *	-0.43 **	–	–	-0.39 •	–	[illegible] **	–					[illegible] **		-0.45 •	-0.31 †
earthworm mass	(Worm)	0.73 ***	[illegible] **	–	0.44	0.41 *	–	–	0.35 *	[illegible] *	0.65 •	-0.45 **	–		0.43 *			-0.42 •		
earthworm species	(WSpp)	–		–	–		– •	-0.41		–	–		– †	0.30			*	-0.35		–
soil air permeability	(AP)	–		–	–		–	–		0.47 •	–	-0.36	–	–	–		–			-0.39 *
soil porosity	(Por)		0.26 t	–	-0.36 *		–	–		–	-0.27 t		0.45 **	–	–	–		0.30 †	[illegible] *	-0.43 *
soil water conductivity	(WC)	-0.52 **	-0.39 *	–	–	-0.54 ***	–	0.35	-0.33 t	-0.30 t	-0.60 ***		0.30 t	-0.59 ***	–	–	–			
soil moisture content	(SM)	-0.30 t	-0.29 t	0.30 t	–	-0.29 t	0.31 t	–		-0.54 ***	–	0.35 *	–	-0.30 †	–	-0.35 *	-0.32	0.35 •		0.67 **
runoff	(RO)	–	-0.49 **	–	0.31 t		0.39 •	–		-0.42 •	–		–	–	–	-0.34 *	-0.42 •	–	0.67 •	

† = P<0.10, * = P<0.05, ** = P<0.01, *** = P<0.001

moisture variables were in general (with the exception of soil water conductivity) not strongly influenced by management treatments, were poorly related to herbage production, and did not explain significant proportions of data set variance. This could be because the variables/measurement techniques we used were not the most appropriate, because the management treatments used were not sufficiently severe to induce large responses in soil physical characteristics, or maybe because soil physical/moisture characteristics are not very useful biophysical indicators.

Conclusions

There has recently been considerable interest in defining "sustainability indicators". Definition of such indicators requires an understanding of ecological processes, of prevailing socio-economic attitudes, and of exactly what is to be sustained. It also requires suitable data sets which can provide insight into resource trends in time, and analytical techniques which can handle inter-related variables with non-linear behaviour.

We conducted analyses of a selected range of vegetation, soil and (on-site) water variables within four areas with different fertiliser/stocking rate histories, in one edaphic/climatic zone. Given the constraints of the techniques used in this preliminary analysis, the two variables which seemed to be the most suitable indicators of biophysical resource status (which in its broad sense includes herbage production) were pasture botanical composition (particularly content of high-fertility responsive grasses and of weed species) and earthworm mass. These are simple and cheap to measure, they are obvious, and responsive to management practices. There is a sound theoretical basis for their use as indicators.

More research is required across a range of environments, and analytical tools need to be developed which permit reliable prediction of resource trends. As potential indicators are identified their usefulness needs to be fully tested before they are employed in resource monitoring programmes. Development of the most suitable indicators requires good understanding of agro-ecosystem function, and hence is likely to be hampered by our current lack of understanding of critical processes.

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