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Early warning indicators of desertification: examples of tests in the Chihuahuan Desert

Amrita G. de Soyza*, Walter G. Whitford†, Jeffrey E. Herrick*, Justin W. Van Zee* & Kris M. Havstad*

**United States Department of Agriculture, Agricultural Research Service & Jornada Experimental Range, New Mexico State University, Dept. 3 JAR, Las Cruces, NM 88003, U.S.A.*
†United States Environmental Protection AgencyNational Exposure Research Laboratory & Characterization Research Division, P.O. Box 93478, Las Vegas, NV 89193, U.S.A.

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Perennial grasslands that dominated the south-west United States during the past 10,000 years have been desertified to varying extents. Desertification is a temporal phenomenon, defined in this paper as a change in the scale of the spatial distribution of resources. We report here on several indicators of desertification, using bare patch indices as surrogates for direct measures. A bare patch index based on canopy cover, which is relevant for precipitation and wind-driven erosion, is not equivalent to another bare patch index based on soil surface measurements, which is relevant for overland water flow-driven erosion. Per cent grass cover, per cent long-lived grass cover, per cent cover of vegetative reproducers, and a relative preference index all yielded sensitive indicators of desertification. The usefulness of some indicators, such as organic litter, depends upon recent environmental history. Other indicators, such as per cent cover due to grazing-resistant species, appear not to be sensitive to desertification and need further development. Range site type may also be important in determining indicator responses, where some indicators were sensitive to a range site while others were not. Overall, we have identified several sensitive indicators of desertification based on vegetational characteristics in varied range sites in the northern Chihuahuan Desert.

Keywords: bare patch index; Chihuahuan Desert; ecosystem health; indicators; litter

Introduction

Desertification in the context of the formerly perennial grass-dominated rangelands of the south-west United States may be defined as a change in scale of the spatial distribution of water, nutrients, and other soil resources. In 'undisturbed' perennial grasslands concentration of soil resources is associated with vertical and horizontal distribution of the dense root mats of grass clumps. The relatively small unvegetated

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spaces between grass clumps result in a relatively homogeneous distribution of resources. The widespread replacement of these grasslands by arid shrublands (York & Dick-Peddie, 1969; Grover & Musick, 1990; Bahre & Shelton, 1993), characterized by more widely spaced resource accumulation points, has resulted in desertification through increased spatial and temporal heterogeneity of soil resources (Schlesinger *et al.*, 1990).

Unfortunately, desertification is more than a mere change in the scale of resource cycling patterns. Desertification often results in a dysfunctional system in which the mean residence time is reduced for resources entering the ecosystem or being produced by it. For example, barren intershrub spaces generate overland flow and provide no impediment to wind. The result is soil erosion and nutrient losses from the ecosystem (van de Ven *et al.* 1989; Takar *et al.*, 1990; Zobeck, 1991). Such situations are indicative of an unhealthy ecosystem, unable to support itself and often leading to accelerated changes in ecosystem community composition and ecosystem dynamics. Therefore, a primary requirement for selecting indicators of ecosystem health is that the indicators must yield information on the functioning of the ecosystem as much as on the physical structure and composition of the ecosystem.

Indicators of desertification are being sought on many fronts, from remote sensing using satellites to ground-based measurements of plant and soil characteristics. Perhaps the greatest impediment to developing sensitive indicators for measuring ecosystem health is the absence of accurately defined thresholds between the three broad categories of healthy, at risk, and unhealthy ecosystems (National Research Council, 1994) Determining thresholds can be a complex process. Historical records for most rangeland sites are rarely available, and when available they usually give information only on the biological and physical state of an ecosystem at a point in time. Correlating measured biological and physical characteristics of an ecosystem directly to ecosystem health is a daunting task. Even if such correlations can be found, the resulting system would probably be so complex as to have little practical use.

A solution to this dilemma may lie in developing indicators of ecosystem function rather than directly linking indicators to ecosystem health (National Research Council, 1994; Herrick & Whitford, 1995). Indicators of ecosystem function are largely independent of historical biases: the indicator merely reflects how well an ecosystem is functioning on the basis of current knowledge of the processes that affect water, nutrient and energy fluxes, and distribution patterns. Second, it is essential not to rely on single indicators. Another major advantage is that because a breakdown in functions usually precedes changes in ecosystem physical structure and composition, indicators of ecosystem function provide an early warning that an ecosystem is in danger of desertification. Sensitive indicators (e.g. de Soyza *et al.*, 1997*a*) can be combined into flexible indices of ecological function and these in turn combined to yield values/objectives such as soil stability and watershed function, production, or biodiversity conservation (see Herrick *et al.*, 1996).

While ecosystem function was not recognized and therefore not measured in historical surveys, current knowledge of vegetational and soil characteristics associated with ecosystem function allow some interpretation of historical records to yield estimates of ecosystem function. Most importantly, knowledge of the history of land use and climate and the degree of ecosystem dysfunction indicated may allow us to detect the probable causes of changes in ecosystem health and perhaps thereby determine the actions needed to halt continued deterioration.

Another feature of sensitive indicators that needs to be considered is the range of environments over which an indicator is effective. If indicator thresholds can be established for a particular ecotype, can they be used in other ecotypes within the same region? If vastly different thresholds are generated for each ecotype, the resulting variability can be confounding and can lead to the development of indicators that are so vague that they are virtually useless. Therefore, a primary requirement for any useful indicator is that its response to changes in ecosystem health be similar over ecotypes in similar range sites within a region.

In this paper we present several examples of sensitive early warning indicators of desertification. Measuring the soil stability and watershed function value of an ecosystem, these indicators were developed and tested using ground-based measurements on several ecotypes in the Jornada Basin of the northern Chihuahuan Desert.

Materials and methods

Study sites

The study sites were on the United States Department of Agriculture, Agricultural Research Service's Jornada Experimental Range (JAR) and on the adjacent Chihuahuan Desert Rangeland Research Center (CDRRC) of New Mexico State University. Both are located in the Jornada Basin of the northern Chihuahuan Desert in southern New Mexico, U.S.A. A total of 33 sites were measured. Six sites consisted of three pairs of long-term grazing exclosures (EXE, EXW, EXNW) established more than 50 years ago, and adjacent grazed areas (EXE-C, EXW-C, EXNW). Another 12 sites were on three grazing gradients (CW_, MW_, and WW_ series), with transects located at 50 (0), 200 (1), 450 (2), and 1050 m (3) from livestock watering points. Four sites were in areas characterized by the National Science Foundations' Jornada Long-Term Ecological Research Program (LTER series).

Eleven sites were in ecotypes dominated by shrubs, including three sites dominated by *Flourencia cernua* (tarbush; TCC, TCH, and TCE), four sites dominated by *Larrea tridentata* (creosotebush; GRR, GRC, GRC2, and GRE), and four sites dominated by *Prosopis glandulosa* (mesquite; BMD, BMC, HMD, and HMC). The shrub sites include several sites where restoration (manipulation) was attempted through chemical and physical methods.

Except for plots within grazing exclosures (EXE, EXW, EXNW, GRC, GRC2, and TCE), all other sites were in pastures intermittently grazed by livestock. All sites were assigned into six categories by the visually dominant cover or whether the site had been chemically or physically modified for rangeland restoration: (1) grass dominated (GRASS), (2) intermediate bare/grass/shrub (MIXED), (3) creosotebush/tarbush dominated (CTSHRUB), (4) mesquite dominated (MSHRUB), (5) bare ground dominated (BARE), and (6) shrub dominated sites manipulated to reverse desertification (MANIPULATED). These sites were further classified according to National Resources Conservation Service (NRCS) range site descriptions. Plots in the following Chihuahuan Desert range sites were evaluated: sandy, deep sand, clayey, loamy, gravelly, and gravelly sand. Plots in the sandy and deep sand range sites were combined into a single category for analysis.

Canopy characteristics

At each site a 100 m × 100 m plot (100 m × 90 m at the exclosures due to exclosure dimensions) was established. These plots were sampled by ten 100 m (90 m in exclosures) transects. The position of each transect line was determined randomly, but a minimum distance of 5 m between lines was maintained. The plots and the transect lines within them were always oriented parallel to the slope. Measurements were made by recording the identity of the plant species or bare patch and the linear intercept of the plant or bare patch (Canfield, 1941; de Soyza *et al.*, 1997*a*). From these data information on the number and size of bare patches and of the vegetative components at each site was extracted. In addition to overall vegetative cover the proportion (as a percentage) of the plot that consisted of long-lived grass, vegetation that resists anthropogenic disturbance, and vegetation that can reproduce vegetatively was also considered. A relative preference index for each site was then calculated.

Soil surface characteristics

On three of the ten 100 m lines, three 10 m segments were randomly chosen, and soil surface characteristics as they relate to soil stability and watershed function were measured. Along the transect segments the distances between and the lengths of intact vegetation at the soil surface, and the width of these obstructions at right angles to the transect line were measured. These are all descriptors of vegetational characteristics that may act as a barrier to the overland flow of water during runoff events. Several other features of the soil surface that affect or reflect resource redistribution, including plant litter, visible cryptogamic crusts, and rock cover were also measured.

Results

Canopy characteristics

Bare soil patches

Data on the size of bare soil patches (soil with no vegetation canopy above it) intercepting our transect lines was extracted and a canopy-based bare patch index calculated (BPI_c) for each site as follows:

$$BPI_c = \text{mean size of bare soil patches} \times \text{proportion bare soil (both based on canopy level measurements)}$$

Our research sites, ranked in sequence of increasing BPI_c, are shown in Table 1. Sites with a high percentage of shrubs and sites near livestock watering points have the greatest BPI_c, whereas sites with grass-dominated vegetation and sites distant from livestock watering points have the lowest BPI_c. Bare patches represent areas where raindrop impact and wind velocities are greatest and where resource loss occurs at the greatest rates. The greater the mean size of bare patches and the greater the proportion of land surface area with no vegetation, the greater the scale of resource heterogeneity in the landscape (= desertification). This close relationship between BPI_c and desertification allows us to use the quantifiable BPI_c indicator to evaluate other indicators of desertification.

Vegetation indicators

Desertification may be reflected in changes in the quantity and composition of perennial plant vegetation. As expected, the overall per cent perennial vegetation canopy cover appears to be correlated with BPI_c, with greatest perennial vegetation cover at low BPI_c and least perennial vegetation cover at high BPI_c (Fig. 1(a)). Sandy range sites had a wide range of BPI_c and per cent perennial vegetation cover, but clayey, loamy, gravelly, and gravelly sand sites appeared to be restricted to an intermediate range of BPI_c and a relatively high range of per cent vegetation cover (Fig. 1(a)).

To investigate whether specific types of perennial vegetation cover could be used as indicators, perennial vegetation cover was further divided into categories of life-form, morphology, and livestock preference. A list of all plant species found at our sites and the subgroupings to which these species were allocated is shown in Table 2.

No clear relationship between per cent shrub cover and BPI_c was found (Fig. 1(b)). Per cent grass cover did appear to be strongly and negatively related to BPI_c, but at sites with BPI_c greater than about 100 the relationship between BPI_c and per cent grass cover becomes less strong (Fig. 1(c)). A large proportion of the total grass cover at a site is due to long-lived grass species (Table 2). As expected, per cent cover due to long-lived grass species was strongly and negatively related to BPI_c (Fig. 1(d)) with a pattern similar to that seen for all grasses (Fig. 1(c)). Many shrub-dominated sites, particularly those in clayey, loamy, gravelly, or gravelly sand range sites also had substantial cover due to grasses (Fig. 1(c, d)).

Table 1. *Study sites arranged in sequence of increasing BPI_c rank. Also shown is the site category, based on dominant vegetation type (grass = GRASS; intermediate bare/grass/shrub = MIXED; creosotebush and/or tarbush = CTSHRUB; mesquite = MSHRUB; bare ground = BARE; manipulated for restoration = MANIPULATED), BPI_s and BPI_s rank*

Site	Category	BPI_c	BPI_c rank	BPI_s	BPI_s rank
LTER-T	CTSGRUB	24·59	1	149·2	13
LTER-G	GRASS	26·27	2	172·3	18
EXE	GRASS	30·16	3	46·30	2
WW3	GRASS	34·35	4	63·57	6
GRR	MANIPULATED	34·93	5	240·8	22
EXW	GRASS	40·23	6	38·10	1
MW3	GRASS	43·67	7	53·73	5
EXNW	GRASS	45·69	8	48·35	3
TCE	MANIPULATED	46·51	9	201·2	19
LTER-C	CTSHRUB	50·21	10	465·3	27
CW3	GRASS	51·21	11	48·89	4
GRE	CTSHRUB	52·70	12	504·5	28
GRC2	CTSHRUB	54·91	13	833·5	32
TCG	MANIPULATED	70·58	14	298·9	24
MW2	MIXED	75·15	15	97·28	7
MW1	MIXED	76·09	16	132·7	10
GRC	CTSHRUB	76·66	17	818·7	31
HMC	MSHRUB	77·45	18	415·5	26
EXNW-C	MIXED	78·58	19	105·6	8
BMD	MANIPULATED	88·91	20	270·6	23
HMD	MANIPULATED	90·44	21	305·0	25
WW2	MIXED	102·9	22	112·9	9
WW1	MIXED	104·7	23	164·9	16
CW1	MIXED	114·0	24	137·3	11
TCC	CTSHRUB	131·4	25	699·4	30
EXW-C	MSHRUB	148·4	26	145·3	12
EXE-C	MIXED	159·3	27	164·7	15
WW0	BARE	164·2	28	205·0	20
LTER-M	MSHRUB	195·5	29	564·4	29
BMC	MSHRUB	229·1	30	855·0	33
CW1	MIXED	259·2	31	167·0	17
MW0	BARE	272·5	32	205·7	21
CW0	BARE	370·8	33	158·6	14

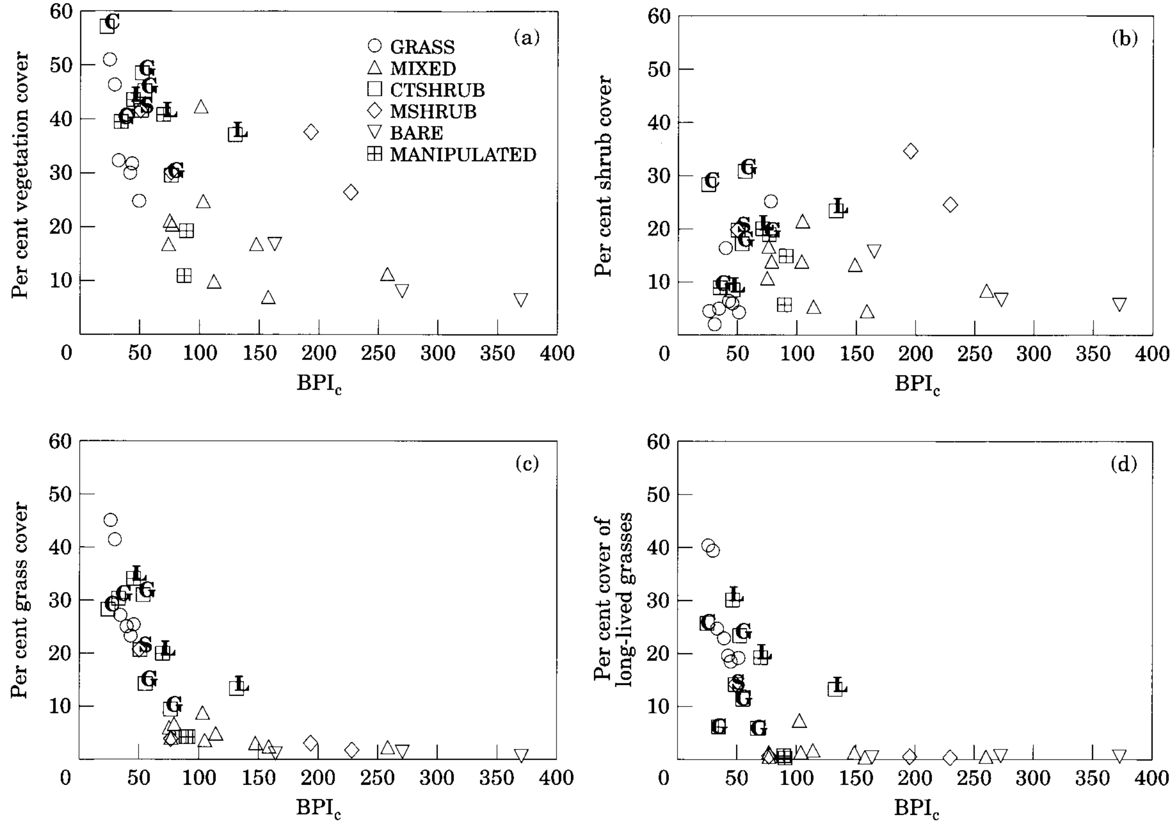

Figure 1. Per cent cover of (a) all perennial vegetation, (b) all shrubs, (c) all perennial grasses, and (d) long-lived grasses only. All indicators are graphed relative to a bare patch index calculated on the basis of canopy level measurements. Symbols with C = clayey range sites, L = loamy range sites, G = gravelly range sites, S = gravelly sand range sites, and symbols without a letter are sandy range sites.

Some plant species have characteristics that may confer resistance or resilience to types of disturbance associated with desertification. An indicator based on the degree of protection from grazing-induced damage for the vegetative meristem of plant species did not appear to be related to BPI_c (Fig. 2(a)). An indicator based on the

Table 2. *List of perennial species showing allocation to subcategories used in indicators. Codes for life-form are the following: long-lived grass = GL, short/medium-lived grass = GS, shrub (including sub-shrubs) = S, succulents = SU, and forbs = F*

Species	Life-form	Grazing resistant	Vegetative reproduction
Acacia constricta Benth.	S		
Acourtia nana (Gray) R. & K.	F	X	X
Aristida purpurea Nutt.	GS		
Aristida ternipes Cav.	GS		
Atriplex canescens (Pursh) Nutt.	S		
Bahia absinthifolia Benth.	F		
Baileya multiradiata Harv. & Gray	F		
Bothriochloa laguroides (DC.) Herter	GS		
Bouteloua curtipendula (Michx.) Torr.	GS		
Bouteloua eriopoda (Torr.) Torr.	GL		X
Cassia bauhinioides Gray	F		
Chaetopappa ericoides (Torr.) Nesom	F		X
Chamaesyce albomarginata (Torr & Gray) Small	F		
Condalia warnockii M. C. Johnston	S		
Croton pottsii (Kl.) Muell. Arg.	F	X	X
Dasyochloa pulchella (Kunth) Stendel	GS		
Ephedra torreyana Wats.	S		
Ephedra trifurca Torr.	S		
Eragrostis lehmanniana Nees	GS		
Flourensia cernua DC.	S	X	
Gutierrezia microcephala (DC.) Gray	S		
Gutierrezia sarothrae (Pursh) Britt. & Rusby	S		
Haplopappus spinulosus (Pursh) DC.	F		
Hoffmanseggia drepanocarpa Gray	F		
Krascheninnikovia lanata (Pursh) Guldenstaedt	S		
Larrea tridentata (DC.) Cov.	S	X	
Lycium pallidum Miers	S		
Melampodium leucanthum Torr. & Gray	F		
Muhlenbergia arenacea (Buckl.) A. S. Hitch.	GS		
Muhlenbergia porteri Scribn.	GL		
Opuntia leptocaulis DC.	SU	X	X
Opuntia phaeacantha Englem.	SU	X	X
Opuntia violacea Englem.	SU	X	X
Parthenium incanum H. B. K.	S		
Pleurphis mutica Buckl.	GL	X	X
Prosopis glandulosa Torr.	S	X	
Scleropogon brevifolius Phil.	GS		
Sphaeralcea spp.	F		
Sporobolus spp.	GS		
Thymophylla acerosa (DC.) Strother	S		
Yucca elata Englem.	S		X
Zinnia spp.	F		X

proportion of canopy cover, however, contributed by species with the ability to produce vegetatively is greatest at sites with low BPI_c, and the cover decreases as BPI_c increases (Fig. 2(b)).

A relative preference index (RPI) for livestock-grazed perennial vegetation at each site was calculated based on all perennial plant species present at a site:

$$RPI = \Sigma(FV \times T_{pal})C$$

where FV = forage value of species (Stubbendieck *et al.*, 1991; good = 1; fair = 0.75; poor = 0.25; none = 0), T_{pal} = proportion of year when species is palatable, and C = canopy cover of plant species. As BPI_c increased, RPI decreased and many shrub-dominated sites, particularly those with non-sandy soils, had relatively high RPI values (Fig. 3).

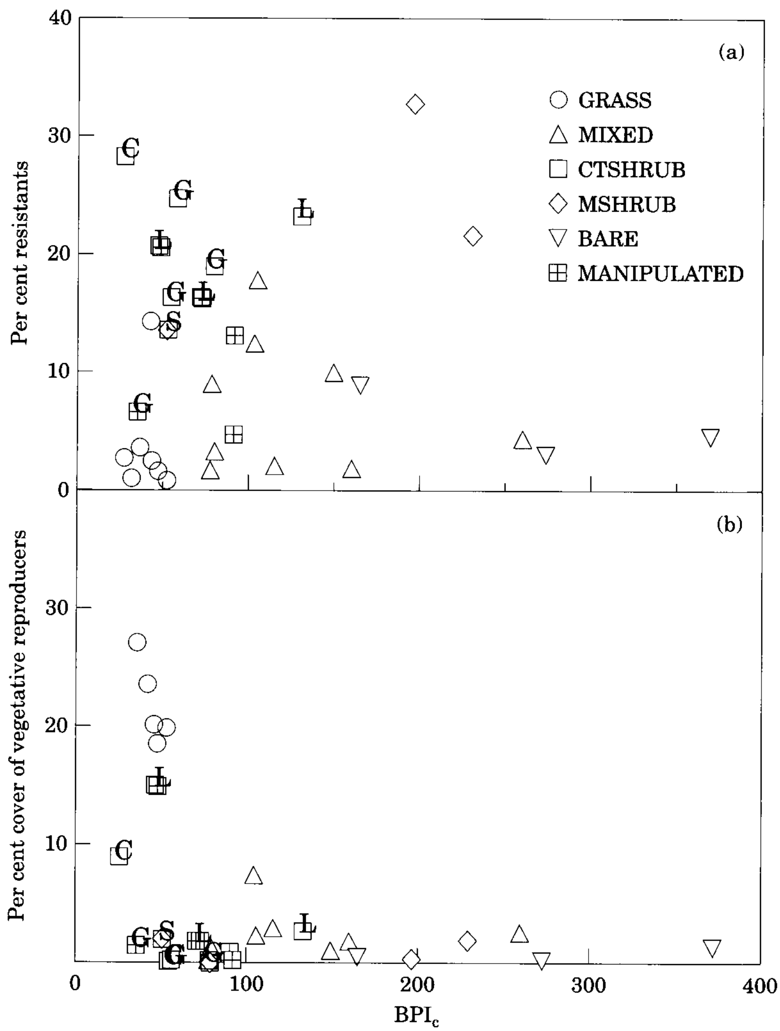

Figure 2. Relationships between BPI_c and vegetative cover calculated on the basis of perennial plant species having morphological characters of (a) ability to resist grazing due to protected meristems and (b) ability to reproduce vegetatively. Symbols with C = clayey range sites, L = loamy range sites, G = gravelly range sites, S = gravelly sand range sites, and symbols without a letter are sandy sites.

Soil surface characteristics

Bare soil patches

A separate bare patch index was calculated from measurements taken at the soil surface: BPI_s = mean size of bare soil patches × per cent bare soil (both based on measurements at the soil surface).

The ranking of sites based on BPI_s is shown in Table 1. The rank of BPI_c appears to be quite different from the BPI_s rank. BPI_s is determined by the size and distribution of obstructions at the soil surface. The non-sandy range sites also displayed a much greater range of BPI_s values (Fig. 4) than they did BPI_c values (Figs 1, 2 and 3).

Another biotic component that may confer resistance to soil erosion consists of visible cryptogamic biological crusts. At the sites studied, cryptogams were rare and occurred only at seven sites, an insufficient number to observe a significant correlation. Even when dead, plant material can afford some protection from soil erosion. Plant litter was measured as the length of litter occurring along the soil surface transect line. When plotted against BPI_s, plant litter yielded a pattern with two distinct clusters of points, each having a negative relationship between total litter and mean surface bare patch size (Fig. 4).

Discussion

The bare patch index appears to work well as an indicator of ecosystem function in the context of describing bare ground available for resource loss. Grass-dominated sites have smaller BPI_c than do the shrub-dominated sandy range sites. Non-sandy range sites and some manipulated sites, notably GRR and TCE, show substantially smaller BPI_c than do their untreated controls (Table 2). Contrary to our expectations, a shrub-dominated site, LTER-T, had the smallest BPI_c. LTER-T is situated in a clayey runon

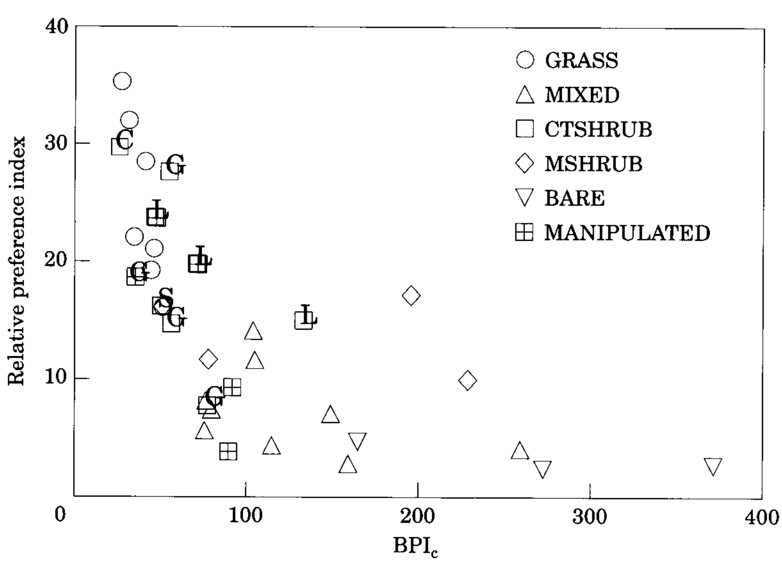

Figure 3. Relationship between a relative preference index (cover due to plants preferred by livestock) indicator and BPI_c. Symbols with C = clayey range sites, L = loamy range sites, G = gravelly range sites, S = gravelly sand range sites, and symbols without a letter are sandy sites.

area where nutrient and water resources accumulate. Although tarbush is the visually dominant biota, the site is very diverse and has a large percentage of grass cover.

An intuitively obvious descriptor of ecosystem condition and desertification, the percentage of a site covered with perennial vegetation (Blackburn & Pierson, 1994), is not the exact inverse of BPI_c. BPI_c combined the mean size of bare patches with the proportion of bare soil at a site and is weighted toward the mean size of bare patches. Per cent canopy cover due to perennial vegetation appears to be related to BPI_c, although some shrub-dominated sites do not fit the expected pattern (Fig. 1(a)). This lack of fit may be explained to some extent by differences in range type and by the fact that not all perennial vegetation types are functionally equal. Per cent shrub cover does not appear to be related to BPI_c (Fig. 1(b)) and is probably not a good early warning indicator of desertification.

The lack of a relationship between per cent shrub cover and BPI_c may cause the weakening of the relationship between per cent (perennial) vegetation cover (of which shrubs are a component) and BPI_c. Some life-forms, such as perennial grasses, may be more efficient at protecting the soil than are most shrubs, forbs, or succulents.

The per cent cover due to grasses, the other major component of perennial vegetation in our system, does appear to be closely related to BPI_c (Fig. 1(c)). As BPI_c increases from about 25 to 100, per cent grass cover rapidly declines, suggesting that per cent grass cover is sensitive to the early stages of desertification. As BPI_c increases further, grass cover changes relatively little. Perennial grass cover can be further divided into long-lived and short-lived life-forms. The long-lived grasses, which persist in the ecosystem for longer periods, also tend to have a more spreading system compared to shorter lived species, which tend to have a more clumped life-form. The per cent long-lived grass cover indicator also appears to be strongly related to BPI_c (Fig. 1(d)) and also may be used as an early warning indicator of desertification.

While the abiotic environment may play an important role in desertification, biological factors such as livestock grazing may also be a driving force for desertification of western rangelands. We considered two potential indicators of resistance to livestock grazing. Perennial plant species with protected meristems

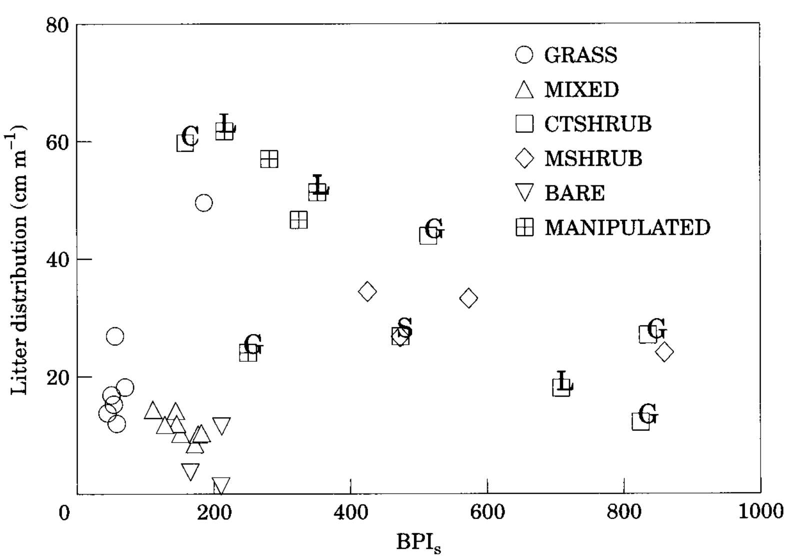

Figure 4. Relationship between BPI_s and litter illustrating the drawbacks of using a transient indicator, despite its potentially important role in ecosystem health. Symbols with C = clayey range sites, L = loamy range sites, G = gravelly range sites, S = gravelly sand range sites, and symbols without a letter are sandy sites.

(growing points) may be able to recover more quickly and increase canopy biomass and cover and thereby afford more protection to the soil. However, when we plotted this indicator against BPI_c, we found no obvious relationship with BPI_c (Fig. 2(a)).

A plant's ability to recover from mortality or severe biomass loss may depend on its ability to recolonize an area from vegetative growing points (as opposed to being entirely seed reproducing). Rapid recolonization will maintain the functional integrity (i.e. prevent desertification) of an ecotype by minimizing resource loss from unprotected soil. The strong negative relationship between per cent cover of vegetative reproducers and increasing BPI_c (Fig. 2(b)) at relatively low values of BPI_c suggests that per cent cover of vegetative reproducers may be a useful and sensitive early warning indicator of desertification in our system.

Another potential livestock grazing related indicator is the proportion of cover due to vegetation preferred as forage by livestock. The relative preference index was strongly and negatively related to increasing BPI_c (Fig. 3). Sites with a high RPI (and a low BPI_c) tended to be grass-dominated ecosystems, suggesting that these sites were the least heavily grazed and the least desertified. However, many shrub-dominated sites also had a high RPI. As shown in Fig. 1, many non-sandy range sites dominated by shrub canopy also had high proportions of grass cover. The relative preference index also appears to be a sensitive early warning indicator of desertification, but, if used, its interpretation must be linked to observations on changes in the species composition of an ecosystem.

Canopy-based measurements such as those discussed above yielded some sensitive indicators of ecosystem function in terms of soil stability and watershed function. However, in terms of how canopy factors function in maintaining soil stability and watershed function, the indicators discussed so far are weighted toward assessing the canopy effects on slowing raindrop impact, wind-driven resource loss, and the effects of anthropogenic disturbance. These indicators do not fully assess the role of overland water flow in resource redistribution.

For indicators of ecosystem deterioration (desertification) due to overland flow, we considered measurements taken at the soil surface. Comparison of a ranking based on BPI_c and BPI_s showed that these two measures of bare patch size are not correlated (Table 2). A site can therefore have very different canopy and soil surface-based resource flow dynamics.

Organic litter on the soil surface can be viewed as an indicator. Unlike the indicators considered thus far, the quantity (length along a transect line) of litter at any site and time can be strongly affected by recent environmental conditions (e.g. de Soyza *et al.*, 1997*b*). The indicators reported in this paper were measured at varied times and over a period of 2 years. The litter indicator shows a clear bimodal distribution that corresponds to the time of measurement. Measurements taken in 1996–1997 found substantially more litter than those taken in 1995–1996. The result is two clusters of points both having a similar negative correlation between litter and BPI_s but with vastly different intercepts (Fig. 4).

Our results suggest that sensitive early warning indicators of desertification can be obtained from relatively simple transect-based measurements of canopy and soil surface characteristics. Canopy measurement-based indicators, including a bare patch index, describe ecosystem condition as it relates to wind- and precipitation-driven resource loss from an ecosystem. Soil surface measurements, on the other hand, describe ecosystem condition as a function of overland flow of water. Not all potential indicators are sensitive to the early stages of desertification. These indicators will be developed further or discarded if their sensitivity cannot be enhanced. Although indicators based on perennial vegetation tend to be more stable over time, all vegetation-based indicators must be assessed relative to (recent) past environmental conditions. We must also consider the range site of the area of interest. Overall, we have developed several sensitive indicators of desertification based on vegetational characteristics. When combined with soil-based indicators being developed, these vegetation-based indicators appear to hold great potential for use at a wider scale as early warning indicators of ecosystem condition for a variety of ecosystems.

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