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The efficacy of TM satellite imagery for rapid assessment of Chihuahuan xeric habitat intactness for ecoregion-scale conservation planning

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A critical step in designing effective conservation landscapes is the identification of relatively intact natural habitats. Satellite remote sensing has been effectively used to distinguish relatively intact and degraded forests at a number of scales. However, the utility of remote sensing data for rapid and cost-effective assessments of habitat intactness across large arid regions has not been adequately tested. To this end, we tested the ability of TM imagery to rapidly discriminate different levels of habitat degradation across large regions of the Chihuahuan Desert. We were able to identify relatively intact habitat in many cases. However, degraded habitat was often misidentified as relatively intact. The use of both mid- and late-season imagery provides some improvement by highlighting phenological differences among the intactness classes. Overall, low vegetation cover and inter- and intra-seasonal variability diminish the utility of TM imagery for large-scale conservation planning in the Chihuahuan Desert.

Keywords: conservation planning; remote sensing; habitat intactness; Chihuahuan Desert

Introduction

The conservation community increasingly recognizes the distinctive and important biodiversity of deserts and other arid ecosystems (Olson & Dinerstein, 1998; Ricketts *et al.*, 1999; Dinerstein *et al.*, 2000). Cost-effective planning tools are needed to help

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develop effective conservation strategies for deserts as these ecosystems face significant threats and we have limited time and resources for their conservation. Conservation planners require information on the distribution and extent of relatively intact desert habitats across ecoregions to identify areas where populations of sensitive species and ecological phenomena are most likely to occur and where they have the best chance for persistence. For example, large predators such as the jaguar (*Panthera onca*) may be more likely to persist in areas where domestic livestock grazing has not reduced forage availability for native prey species, or where there is sufficient area of natural habitat to support a viable population over the long term (Sanderson *et al.*, in press). Some rare cacti or plant communities may only survive in areas that have not been exposed to extensive trampling by livestock (Anderson *et al.*, 1994). In addition, these relatively intact habitats may ultimately form the core of protected area networks and determine types of land use and restoration efforts necessary in different zones. For these reasons, a method to rapidly assess the intactness of non-forest habitats over whole ecoregions would be an invaluable tool for conservation planning.

Remote sensing data have been used to measure intact and converted forests across large regions (Skole & Tucker, 1993; NASA, 1998). Detailed classification and ground-truthing of imagery has also produced accurate habitat maps and assessments of habitat quality at individual sites in forest and non-forest ecosystems such as grasslands, deserts, and coastal marine habitats (Sader *et al.*, 1991; Kremer & Running, 1993; Lauver, 1997). However, the efficacy of remote sensing tools for rapidly assessing the relative intactness of non-forest habitats across entire ecoregions (50 000–300 000 km^2) has not been tested, particularly within the context of biodiversity features rather than range conditions. Here we test the efficacy of a commonly used and widely available remote-sensing data source, Landsat Thematic Mapper (TM), for rapidly mapping the relative intactness of two broad habitat types in the Chihuahuan Desert over larger landscapes.

Previous methods used for mapping xeric habitat intactness

Satellite-borne remote sensing has a long history of application to arid-lands ecological research (Tueller, 1987). Previous workers have utilized numerous sensors, including the advanced very high resolution radiometer (AVHRR), for measuring desert spatial extent (Tucker & Justice, 1986), monitoring desertification (Tucker *et al.*, 1991), mapping vegetation (Kremer & Running, 1993; Peters *et al.*, 1997), vegetation change over time (Warren & Hutchinson, 1984), and habitat degredation (Eve, 1995). AVHRR's high temporal resolution and coarse spatial resolution enable one to frequently image large areas with relatively low data volume. However, its coarse spatial resolution (1·1 km pixel as opposed to ˜30 m for Landsat TM) make it less suitable for measuring fine-scale land-cover changes resulting from overgrazing and loss of riparian habitats, significant factors leading to habitat degradation and biodiversity loss in xeric environments.

Others have used high-resolution satellite data to map plant communities at the site level (Franklin *et al.*, 1993), to map grassland species diversity (Lauver, 1997), and to identify 'natural' grassland areas (Lauver & Whistler, 1993) in a single county in Kansas. These studies demonstrate the utility of high-resolution sensors for vegetation mapping at local scales. Few studies exist, however, which test these applications at the ecoregional scale. Brazilian Cerrado savannas have recently been mapped at large scales using a combination of TM and radar imagery (CABS, 2000), but the vegetative cover in this habitat is typically more pronounced than in deserts. In addition, few have approached arid-lands remote sensing research from a standpoint of the intactness of native biotas and habitats, concentrating instead on 'range' features, or in some cases 'ecosystem health' (Milton & Dean, 1996). Finally, xeric habitat loss is typically viewed in the context of increasing shrub-cover, ignoring the potential occurrence of relatively intact, natural, desert-scrub communities.

In the Chihuahuan Desert, few data exist to adequately categorize desert habitat intactness. Brown's (1994) map broadly characterizes potential natural vegetation communities in the Southwestern United States and Northern Mexico. Other research has coarsely characterized botanical features of the Chihuahuan desert (Johnston, 1977; Henrickson & Johnston, 1986). In another study, the Instituto Nacional de Estadística, Geografía e Informática (INEGI, 1998) used AVHRR, ground-truthing, and interpretation by regional experts to classify Mexico into approximately 180 land-cover classes. Within the Chihuahuan Desert, we categorized the descriptors for these 180 classes into three major intactness categories: heavily altered (e.g. urban or converted, agricultural), altered (i.e. degraded), and relatively intact (i.e. natural to semi-natural habitats). Mapping these three intactness categories results in extensive portions of the ecoregion being covered by the last category, which might be interpreted as relatively intact (Fig. 1). However, initial ground-truthing and consultations with regional experts (Dinerstein *et al.*, 2000) suggest that most of the area covered under these categories is better classified as altered (degraded) to highly altered. Thus, this mapping effort has limited value for conservation planning, largely because habitat degradation and biodiversity features were not used or emphasized in the classification process. Further, this classification also does not qualify as a rapid assessment analysis as it required several years and extensive resources to complete.

We asked regional experts at a Chihuahuan Desert conservation workshop (Dinerstein *et al.*, 2000) to identify larger areas (50–500+ km^2) within the ecoregion that harbored particularly intact habitats and to evaluate the relative intactness of different priority areas (Fig. 1). The information provided by the experts was deemed accurate and detailed for sites well known to individuals, and adequate for designing broader conservation landscapes for certain priority areas. However, there was a sufficient level of uncertainty regarding the existence or location of other relatively intact natural habitats throughout the ecoregion to explore the possibility of rapid mapping of these habitats at the scale of whole basins and ranges using TM data. Some of the areas identified as intact by the experts are also likely to contain heterogeneous landscapes of intact, altered (degraded), and highly altered habitats at finer scales.

Defining intactness

We define relatively intact habitat as relatively undisturbed areas that still support natural ecological processes (e.g. disturbance regimes, seasonal movements of species) and harbor natural communities with most of the original assemblage of native species present within their range of natural abundances. Altered habitats are more impacted by human disturbance but retain the potential to sustain native species and processes. Heavily altered habitat represents areas that have been degraded to the point of retaining little or no potential value for biodiversity conservation without long-term and extensive restoration. As virtually all of the Chihuahuan desert has been altered in some way since the arrival of humans, there are no longer any truly intact areas. Therefore, this work can only consider the relative degradation of the habitats in question. Below we characterize each of these intactness levels in more detail for xeric ecosystems.

Relatively intact: The habitat has not been plowed, chained, or altered by major changes in hydrologic patterns. The full suite of native plant species is still present, each in abundance within its natural range of variation, and successional patterns follow natural cycles (e.g. grazing by domestic livestock has not had a significant impact on species compositions or seral stages). Natural fire regimes are still present.

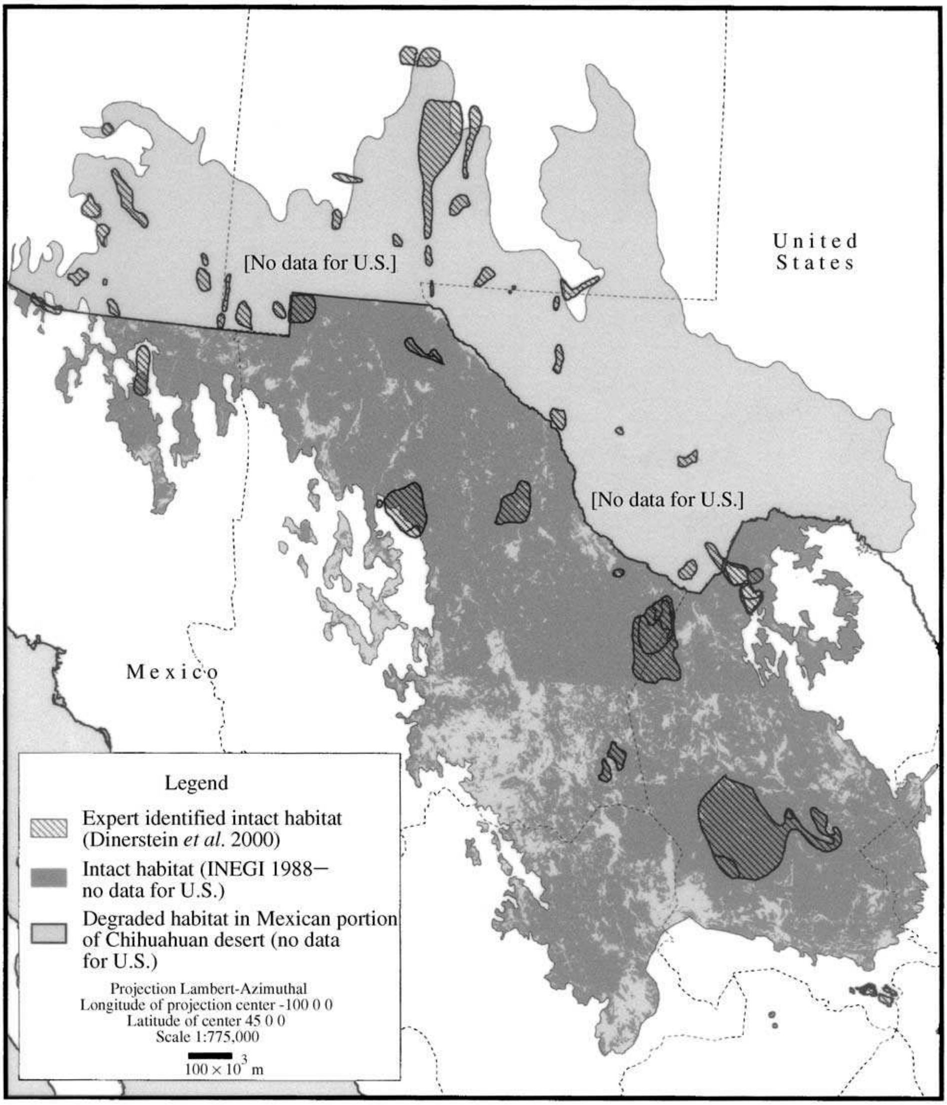

Figure 1. Two sources of existing intactness data for Chihuahuan desert.

Although large mammal and bird populations may presently be absent from some blocks of habitat due to exploitation, insufficient area, or diminished resources, such blocks may still sustain many native communities and populations of plant, invertebrate, and vertebrate species, as well as their associated ecological processes (Fig. 2(a,b)).

Altered (*degraded*)*:* Heavy grazing has altered dominance patterns of plant species. Some exotic species are present and surface water patterns may be altered, but the substrate has not been physically disturbed. Natural fire regimes have been significantly altered. Original habitat is likely to return with time, moderate restoration, and adequate source pools of native species.

Heavily altered: Habitat is almost entirely altered by human development, plowing, chaining, and burning. Native species have been almost entirely replaced by exotics.

Figure 2. Examples of intact (a) and degraded (b) desert grassland (photos T. Allbutt).

Surface water patterns have been extensively altered. Natural fire regimes have been significantly altered. In some cases there can be total or near-total conversion of native habitat to human-dominated landscapes such as urban areas, settlements, and agricultural zones (Fig. 3(a,b)).

Specific ecological and physical features used to measure relative intactness at field sites are described under Methods and materials and in Table 3.

Figure 3. Examples of intact (a) and degraded (b) desert scrub (photos C. Loucks).

Methods and materials

Intactness assessment

Different habitat intactness conditions might be discriminated using satellite imagery by identifying distinct spectral values associated with alteration of vegetation cover and structure, plant species compositions, or alteration of exposed soils due to erosion, trampling, burning, or other forms of physical disturbance. Furthermore, varying levels of intactness may be evident seasonally, assuming that relatively intact and degraded communities may exhibit different phenological responses over the course of a growing season.

The key question for regional scale planning purposes is whether these data are effective predictors from one area to another despite potential spectral variation caused by differences in bedrock, soil types, soil moisture, soil features, erosion features, topography, season, sun-angle, aspect, and view-angle. We know satellite information can be useful for assessing variation in habitat intactness for different habitat types within sites (areas ranging from several kilometers to 100 km^2) with extensive ground-truthing and manual image manipulation. But does the predictive value of these classifications hold when applied across whole basins, multiple basins, or entire desert ecoregions? The significance of confounding variables is likely to increase at broader scales as the range of biophysical features and ecological conditions expands beyond that experienced by single sites and as the grain of the analysis becomes coarser.

This study tests the predictive value of TM for assessing relative habitat intactness for multiple sites across several basins. We focused on two widespread and important habitat types of the Chihuahuan Desert, desert grassland and desert scrub, in order to reduce the influence of habitat type on satellite response.

Desert grasslands and scrub

Middle and lower elevation communities in the Chihuahuan Desert can be broadly categorized into two types: desert grasslands and desert scrubs. Desert and semi-desert grasslands once dominated many Chihuahuan basins with desert scrub on the margins and hillsides. These formerly extensive grasslands support a rich fauna of herbivores and predators, including pronghorn (*Antilocapra americana*), black-tailed and Mexican prairie dog (*Cynomys ludovicianus* and *C. mexicanus*) colonies, various small predators, and now-extirpated wolves (*Canis lupus*), bison (*Bison bison*), and brown or Mexican grizzly (*Ursus arctos*) bears (Wilson & Ruff, 1999). Most basins are now dominated by 'disclimax' desert scrub (Brown, 1994) due to centuries of degradation. Native desert scrub communities often contain a significant grass component. Where they are relatively undisturbed they often host diverse plant communities with many local endemics restricted to single basins or even hillsides, particularly for cacti (Hernández & Bárcenas, 1995, 1996).

Methods for assessing the value of TM data for mapping relative habitat intactness

We utilized two approaches for testing the relationship between the TM imagery and the field-derived intactness data: image classification of single-date imagery, and an analysis of early- and late-season image ratios.

Image classification of single-date imagery

The first method employed relatively standard image classification methods in order to develop predictive maps of relatively intact habitat, by extrapolation from our known study areas. The results were then tested using accuracy assessments of the resulting maps, as well as field checking of predicted relatively intact sites. All of the processing was performed using PCI's EASI/PACE and Imageworks software (Silicon

Graphics workstations at NASA Goddard Space Flight Center). Several steps are involved in this approach:

1. Experimental design
2. Data acquisition
3. Initial registration and unsupervised classifications
4. Initial field visit
5. Georectification
6. Field data organization and input
7. Band selection
8. Unsupervised image clustering
9. Supervised classification
10. Accuracy assessment
11. Field testing

Experimental design: We attempted to maximize the number of sites per intactness class and per habitat type in order to have as many training and testing pixels as possible, given time and logistical limitations. According to Jensen (1996), the rule of thumb for n bands is to select at least $10n$ training pixels per class. Therefore, for the five band classifications (Band selection, below), there should be at least 50 pixels per class. Reaching this threshold required the grouping of habitat types into desert scrub and desert grassland, and intactness levels into two: relatively intact or relatively degraded. Furthermore, wherever possible, training sites and test sites were selected in separate basins to test the ability of the classifications to predict relative intactness in disparate sites.

Data acquisition: Landsat TM-NLAPS format data from the EROS data center were used (Table 1). The data were atmospherically and radiometrically corrected by EROS data center. The images were predominantly cloud free and were acquired in late spring and mid-summer of 1995.

Initial registration and unsupervised classifications: Prior to the first field visit the images were roughly registered to topographic maps, and clustered using the unsupervised ISODATA algorithm. Maps of the raw imagery and these initial clusters were brought to the field, to allow a preliminary assessment of the ability of the imagery to distinguish on-the-ground features.

Initial field visit: We visited several dozen Chihuahuan Desert field sites in June 1998 with field biologists, ranking each site for several biological and biophysical variables in order to derive an overall ‘intactness’ score for each (Tables 2 and 3). Ground control points for registration of the images were also recorded.

Georectification: The images were more accurately georectified using ground control points collected at road intersections and other identifiable points in the field. This step increases the accuracy of field site location on the imagery.

Table 1. *TM data used in analysis*

Path/Row	Acquisition Date	Scene ID
Single-date analyses		
029/041	07-July-95	LT5029041009519210
030/041	29-April-95	LT5030041009511910
Multi-date analysis		
030/041	18-April-97	LT5030041009710810
030/041	25-September-97	LT5030041009726810

Table 2. *Location and relative intactness scores for field sites*

Site name	Date	Mean longitude	Mean latitude	Habitat type*	Indicator species (0–5)	Soil features (0–5)	Erosion features (0–5)	Structure & cover (0–5)	Total Score (4–20)
Scrub-1	Jun-98	26·9101	102·1205	S-A2	3	3	4	2	12
Scrub-2	Jun-98	26·8805	102·0951	S-A1	4	3	2	3	12
Scrub-3	Jun-98	26·9767	102·1056	S-A2	3	2	1	2	8
Scrub-4	Jun-98	26·9514	102·1764	S-A2	3	1	1	1	6
Scrub-5	Jun-98	26·9280	102·3376	S-A1	1	1	1	2	5
Scrub-6	Jun-98	27·1795	102·2624	S-A1	3	2	2	2	9
Scrub-7	Jun-98	27·3094	102·4300	S-A2	4	3	3	3	13
Scrub-8	Jun-98	27·3097	102·4717	S-A1	3	2	2	3	10
Scrub-9	Jun-98	27·2850	102·6087	S-B	4	2	2	3	11
Scrub-10	Jun-98	27·2771	102·6250	S-A1	3	1	1	2	7
Scrub-11	Jun-98	27·2621	102·7452	S-A2	3	3	2	4	12
Scrub-12	Jun-98	27·2698	102·7550	S-B/S-A1	3	2	2	3	10
Scrub-13	Jun-98	27·2710	102·8058	S-A1	2	1	1	1	5
Scrub-14	Jun-98	27·9802	103·5657	S-A2	3	2	3	3	11
Scrub-15	Jun-98	26·1679	102·7429	S-A1	4	2	2	3	11
Scrub-16	Jun-98	26·1568	102·7583	S-A1	4	2	2	3	11
Scrub-17	Jun-98	26·1022	102·7283	S-B/S-A1	3	2	1	3	9
Scrub-18	Jun-98	26·5349	102·4621	S-B/S-A1	4	3	2	4	13
Scrub-19	Jun-98	26·6004	102·3314	S-A2	3	3	2	2	10
Scrub-20	Jun-98	26·6429	102·1931	S-B	3	2	2	3	10
Scrub-21	Jun-98	26·7689	102·1545	S-B/S-A1	3	2	2	3	10
Scrub-22	Jun-98	26·8178	102·1438	S-A1	3	1	1	3	8
Scrub-23	Jun-98	26·8703	102·0870	S-B/S-A2	3	3	2	4	12
Scrub-24	Jun-98	26·9088	102·1194	S-A2	3	2	2	3	10
Grass-1	Jun-98	26·9510	102·1025	G-B	4	4	3	2	13
Grass-2	Jun-98	26·8949	102·0816	G-B	5	5	4	5	19
Grass-3	Jun-98	27·2890	102·9459	G-C	3	2	3	2	10
Grass-4	Jun-98	27·2936	102·9632	G-C	4	3	3	4	14
Grass-5	Jun-98	28·0028	103·1951	G-B	3	3	4	2	12

Table 2 (*continued*)

Site name	Date	Mean longitude	Mean latitude	Habitat type*	Indicator species (0–5)	Soil features (0–5)	Erosion features (0–5)	Structure & cover (0–5)	Total Score (4–20)
Grass-6	Jun-98	27·9682	103·4095	G-C	3	2	3	3	11
Grass-7	Jun-98	29·0423	106·3247	G-A	2	2	2	2	8
Grass-8	Jun-98	29·2664	106·3953	G-A	4	4	3	4	15
Grass-9	Jun-98	29·2678	106·3989	G-A	3	3	3	3	12
Grass-10	Jun-98	29·2692	106·3673	G-A	3	4	2	3	12
Grass-11	Jun-98	29·2711	106·3421	G-B	5	5	5	5	20
Grass-12	Jun-98	29·3653	106·4074	G-A	3	2	2	3	10
Grass-13	Jun-98	29·5902	106·5047	G-A	3	3	3	3	12
Grass-14	Jun-98	29·5180	106·4359	G-C	2	2	2	3	9
Grass-15	Jun-98	25·1369	101·0535	G-A	4	3	4	3	14
NewS-1a Tom	Oct-98	27·0696	101·9042	S-B	4	1	2	4	11
NewS-1a Ric	Oct-98	27·0696	101·9045	S-B	4	1	2	4	11
NewS-1b	Oct-98	27·0684	101·9052	S-B	4	1	2	4	11
NewS-1c	Oct-98	27·0723	101·9064	S-B	4	1	2	4	11
NewS-1d Tom	Oct-98	27·0705	101·9037	S-B	4	1	2	4	11
NewS-1d Ric	Oct-98	27·0701	101·9035	S-B	4	1	2	4	11
NewS-2a Tom	Oct-98	27·1183	101·9050	S-H	2	1	1	2	6
NewS-2a Ric	Oct-98	27·1179	101·9050	S-H	2	1	1	2	6
NewS-2b	Oct-98	27·1164	101·9049	S-H	2	1	1	2	6
NewS-2c	Oct-98	27·1165	101·9070	S-H	2	1	1	2	6
NewS-2d	Oct-98	27·1193	101·9062	S-H	2	1	1	2	6
NewS-2e	Oct-98	27·1193	101·9048	S-H	2	1	1	2	6
NewS-3a Tom	Oct-98	27·1575	101·9250	S-H	1	1	1	2	5
NewS-3a Ric	Oct-98	27·1577	101·9245	S-H	1	1	1	2	5
NewS-3b	Oct-98	27·1573	101·9267	S-H	1	1	1	2	5
NewS-3c	Oct-98	27·1587	101·9264	S-H	1	1	1	2	5
NewS-4a	Oct-98	27·0410	101·8919	S-A1	3	2	2	3	10
NewS-4b	Oct-98	27·0407	101·8917	S-A1	3	2	2	3	10

NewS-4c	Oct-98	27·0425	101·8919	S-A1	3	2	2	3	10
NewS-5a Tom	Oct-98	26·8605	102·0755	S-A1	3	1	2	3	9
NewS-5a Ric	Oct-98	26·8602	102·0744	S-A1	3	1	2	3	9
NewS-5b	Oct-98	26·8583	102·0755	S-A1	3	1	2	3	9
NewS-5c	Oct-98	26·8603	102·0757	S-A1	3	1	2	3	9
NewS-6a Tom	Oct-98	26·8493	101·0703	S-A1	4	1	1	4	10
NewS-6a Ric	Oct-98	26·8493	101·0704	S-A1	4	1	1	4	10
NewS-6b	Oct-98	26·8477	101·0713	S-A1	4	1	1	4	10
NewS-6c	Oct-98	26·8464	101·0711	S-A1	4	1	1	4	10
NewS-6d	Oct-98	26·8482	101·0695	S-A1	4	1	1	4	10
NewS-7a Tom	Oct-98	26·8308	102·0599	S-A2	4	2	3	4	13
NewS-7a Ric	Oct-98	26·8303	102·0648	S-A2	4	2	3	4	13
NewS-7b	Oct-98	26·8302	102·0605	S-A2	4	2	3	4	13
NewS-8a Tom	Oct-98	26·9819	102·0990	S-A2	1	1	1	2	5
NewS-8a Ric	Oct-98	26·9813	102·0993	S-A2	1	1	1	2	5
NewS-8b	Oct-98	26·9835	102·1004	S-A2	1	1	1	2	5
NewS-8c	Oct-98	26·9800	102·1005	S-A2	1	1	1	2	5
NewS-9	Oct-98	27·0521	102·2251	S-A1	2	2	1	2	7
NewS-10a	Oct-98	27·3077	102·4616	S-A1	3	2	2	2	9
NewS-10b	Oct-98	27·3080	102·4604	S-A1	3	2	2	2	9
NewS-10c	Oct-98	27·3087	102·4613	S-A1	3	2	2	2	9
NewS-10d	Oct-98	27·3085	102·4612	S-A1	3	2	2	2	9
NewS-10e	Oct-98	27·3077	102·4622	S-A1	3	2	2	2	9
NewG-1a	Oct-98	27·2610	102·6661	G-B	4·5	4·5	5	5	19
NewG-1b	Oct-98	27·2596	102·6658	G-B	4·5	4·5	5	5	19
NewG-1c	Oct-98	27·2609	102·6666	G-B	4·5	4·5	5	5	19
NewG-1d	Oct-98	27·2609	102·6666	G-B	4·5	4·5	5	5	19
NewG-2a	Oct-98	27·2864	102·9381	G-C	4	1	1	2	8
NewG-2b	Oct-98	27·2889	102·9386	G-C	4	1	1	2	8
NewG-2c	Oct-98	27·2885	102·9387	G-C	4	1	1	2	8
NewG-3a	Oct-98	27·4342	103·0486	G-B	5	1	4	3	13
NewG-3b	Oct-98	27·4359	103·0482	G-B	5	1	4	3	13
NewG-3c	Oct-98	27·4360	103·0474	G-B	5	1	4	3	13
NewG-3d	Oct-98	27·4353	103·0470	G-B	5	1	4	3	13

Table 2 (*continued*)

Site name	Date	Mean longitude	Mean latitude	Habitat type*	Indicator species (0–5)	Soil features (0–5)	Erosion features (0–5)	Structure & cover (0–5)	Total Score (4–20)
NewG-4a	Oct-98	27·9662	103·4171	G-C	4	2	4	3	13
NewG-4b	Oct-98	27·9666	103·4178	G-C	4	2	4	3	13
NewG-4c	Oct-98	27·9664	103·4169	G-C	4	2	4	3	13
NewG-5a	Oct-98	28·0306	103·2167	G-B	5	1	3	2	11
NewG-5b	Oct-98	28·0243	103·2224	G-B	5	1	3	2	11
NewG-5c	Oct-98	28·0248	103·2232	G-B	5	1	3	2	11
NewG-5d	Oct-98	28·0258	103·2223	G-B	5	1	3	2	11
NewG-6a	Oct-98	28·0156	103·2191	G-B	4	1	4	3	12
NewG-6b	Oct-98	28·0145	103·2198	G-B	4	1	4	3	12
NewG-6c	Oct-98	28·0157	103·2202	G-B	4	1	4	3	12
NewG-7	Oct-98	27·9907	103·1826	G-B	4	3	3	4	14
Validation-1	Oct-98	27·2931	102·9597	G-C	3	1	2	2	8
Validation-2	Oct-98	27·2944	102·9639	G-C	1	1	1	1	4
Validation-3	Oct-98	27·3000	102·9611	G-C	3	2	3	2	10
Validation-4	Oct-98	27·2944	102·9583	G-C	1	1	1	1	4
Validation-5	Oct-98	27·2972	102·9639	G-C	3	1	2	2	8
Validation-6	Oct-98	28·0000	103·2472	G-C	1	2	4	1	8
Validation-7	Oct-98	28·0028	103·2472	G-C	1	2	4	1	8
Validation-8	Oct-98	28·0000	103·2444	G-C	1	2	4	1	8
Validation-9	Oct-98	27·9944	103·2417	G-C	1	1	4	1	7
Validation-10	Oct-98	27·9917	103·2389	G-C	3	2	3	1	9

*Key to habitat types listed above: *Desert scrub*: S-A1—Chihuahuan Desert scrub: Larrea scrub (gobernadora), S-A2—Chihuahuan Desert scrub: mixed desert scrub (chaparillo), S-B—Lechugilla scrub (lechugillal), S-H—submontane mattoral. *Desert grassland*: G-A—Gramma grasslands (pastizal de grama o navajita), G-B—Sacaton grassland (zacatonal), G-C—Tobosa grassland (Pastizal de tobosa).

Table 3. *Field assessment of intactness features*

The following feature categories (scores reported above) were evaluated at each site:	
• indicator plant species (indicator species)	
• presence of living soil crusts & plant litter (soil features)	
• absence of fire or grazing induced erosion features such as pedestals, rills, terraces, mineral crusts, evident impact on plants (erosional features)	
• percentage ground cover of characteristic species (structure and cover)	
In each feature category, scores were developed from the following criteria:	
Indicator native plant species and presence of introduced species	
3 or more native spp.	5 points
Presence of 2 or more	3 points
Presence of 1	1 point
Presence of living soil crusts & plant litter	
Relatively intact crust & litter	5 points
50–75% intact	3 points
25–49% intact	1 point
Grazing induced erosional features such as pedestals, rills, terraces, mineral crusts	
No presence of features	5 points
Medium level of features	3 points
High level of features	1 point
Percentage ground cover of characteristic species	
75–100%	5 points
50–75%	3 points
25–50%	1 point

Points	Intactness status
Total scores indicate the following intactness levels in a four-class scheme:	
0–4	Altered
5–9	Degraded
10–14	Partially degraded
15–20	Relatively intact
These values were lumped into two classes for the purpose of classification:	
0–9	Relatively degraded
10–20	Relatively intact

Field data organization and input: Field sites were georeferenced on the imagery and used as training sites for band selection and supervised classification. Because there are few (generally <100) training pixels for each intactness class, all grass and scrub sites are therefore grouped together, and the mean intactness score used as thresholds for two intactness categories: relatively intact *vs.* relatively degraded.

Band selection: Discriminant analysis was used to identify the band combinations best able to separate the field-measured intactness scores. All raw bands (minus band 6) plus several derived ratios, including principal components, brightness, greenness, normalized difference vegetation index (NDVI) and soil-adjusted vegetation index (SAVI), were tested in a set of standard combinations known to be useful from previous studies (Duncan *et al.*, 1993; Lauver, 1997). For both the scrub and grass sites, the best separation was provided by bands 2 and 7, eigenvectors 1 and 2, brightness, and NDVI.

Unsupervised image clustering: Raw images were classified using the unsupervised ISODATA algorithm. These clusters were then assigned a value of grass, scrub, or neither, based on habitat information obtained during field testing. These clusters served as masks during the supervised classification. This represents a primary discrimination of the data, essentially reducing the choices available for classification in subsequent steps.

Supervised classification: Approximately two-thirds of the field data training sites (Table 2) were used to classify the image within the grass or scrub clusters created. The grass training data was used only under the grass mask, and the scrub data only under the scrub mask. The result is a map of relatively intact/degraded scrub habitat, relatively intact/degraded grass habitat, or neither.

Accuracy assessment: Data from the remainder of the field sites was used to test the accuracy of predicted intactness levels of the image classification (Table 1).

Field testing: In October 1998, we performed a field check of ten sites chosen randomly within predicted intact areas (Fig. 4).

Analysis of early- and late-season imagery

Testing the hypothesis that we could use seasonality to better separate the various levels of intactness, we attempted to use seasonal changes evident in a spring *vs.* a fall image in order to identify areas of relatively intact grass. To explore this relationship, regression analyses between the field-measured intactness and several image-derived variables were performed on several sets of spring and fall images of the same localities (Table 1). The regressions were of two types: between the field data and band radiance values, and between the field data and seasonal NDVI ratios. First, the digital numbers for bands 2–5 were converted to radiance values for both spring and fall images. Radiance is a measurement of the electromagnetic energy received at the sensor, and thus is a more physical measurement of ground conditions than are the digital numbers available in the image itself. Regressions were performed between the radiance values and the field-measured intactness values.

Second, we performed regressions between the field-measured intactness and the fall-to-spring NDVI ratio. NDVI is a measurement of total photosynthetic activity (Tucker, 1979). NDVI has been used with the data from many different remote-sensing platforms, to assess everything from crop health and desertification, to mapping vegetation and deforestation (Justice *et al.*, 1985; Tucker *et al.*, 1985; Townshend *et al.*, 1993). Generally, higher NDVI values indicate more active photosynthesis in a given pixel. Grasses in xeric ecoregions are generally C_4 plants, therefore they tend to green-up in the fall following the late-season monsoon rains. In desert scrubs, however, C_3 species are more common, and tend to be more green in the spring. Therefore, a high fall-to-spring NDVI value might indicate a pixel that is

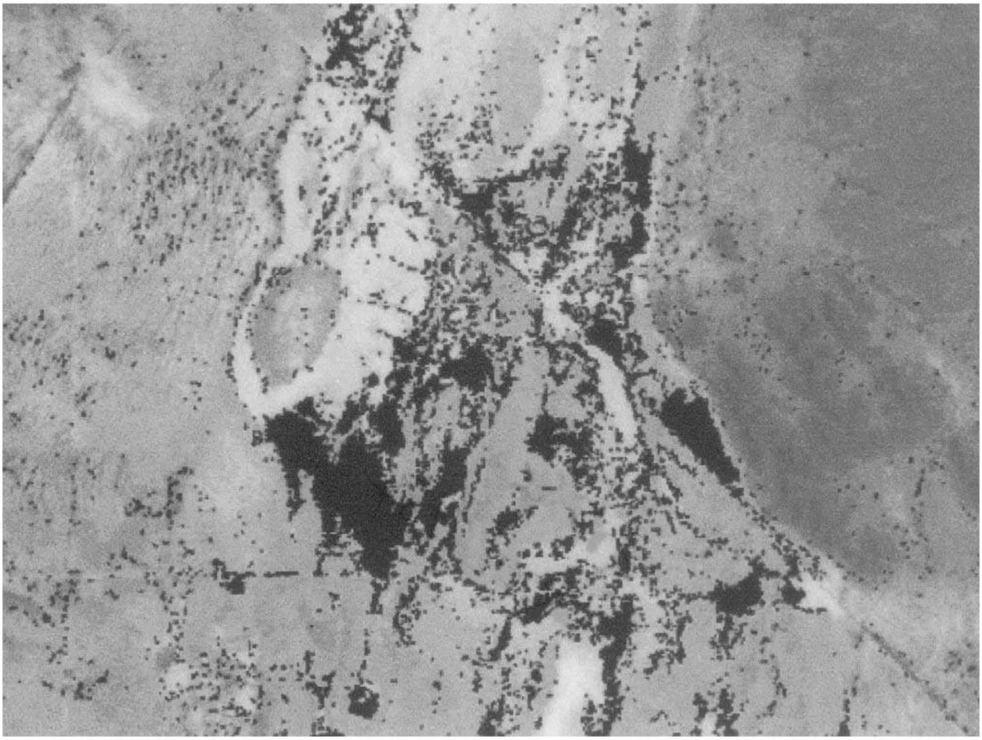

Figure 4. Map showing areas of predicted intact grassland in black. Grayscale TM band 2 in background.

(a) Spring 1997 (b) Fall 1997 (c) Fall/springNDVI ratio

Figure 5. (a–c) These three figures illustrate seasonal differences evident in the imagery. The first two are raw TM images of the same area in Spring and Fall, respectively. The third is a ratio of the Fall to Spring NDVI values for each image. In the NDVI ratio, brighter areas indicate a stronger NDVI response in the Fall relative to the Spring. Likewise, darker areas indicate a stronger NDVI in the Spring relative to the Fall.

more green, more photosynthetically active in the fall, and therefore dominated by a vigorous growth of grasses.

There are clear differences in reflectance apparent between the two images (Fig. 5(a), (b)). Similarly, the fall-to-spring NDVI ratio image (Fig. 5(c)) shows certain areas that exhibit a negative ratio, and others that are positive. The brighter areas exhibit positive fall-to-spring photosynthetic activity and therefore may be indicative of healthy and relatively intact grasses. The darker areas, on the other hand, have negative fall-to-spring NDVI values, and therefore should either be dominated by shrubs, or degraded grasses. Regressions were performed between the field-measured intactness and these NDVI values in order to test this theory.

Results

Results of image classification of single-date imagery

The initial accuracy assessment results are presented in Table 4. While the results are highly accurate for certain classes, such as relatively intact grass, the overall accuracy is not very good.

Furthermore, with respect to the relatively intact scrub classification, field validation of the predicted intactness map revealed that it was clearly grossly over-predicting relatively intact scrub. Nearly, the entire potential scrub area was classified as relatively intact, although field inspections revealed most of the habitat was degraded to some degree. Nevertheless, the relatively intact grasslands warranted further inspection, given the relatively good accuracy statistics, and the appearance of the resulting predicted relatively intact grassland map (Fig. 4).

A field visit was undertaken in October 1998 to test the accuracy of the predicted grassland map. Ten sites were chosen randomly within larger predicted relatively intact polygons. Only one of ten was correctly predicted as relatively intact, site Validation-3 (Table 2).

Table 4. *Accuracy assessment statistics for single-date analyses*

Class	Pixels	0	1	2
Grassland				
Relatively intact grass	18	5·6	94·4	0·0
Degraded grass	42	28·6	26·2	45·2
Average accuracy	69·84%			
Overall accuracy	60·00%			
Kappa coefficient	0·37337			
S.D.	0·08923			
Confidence level:				
99% 0·37337 ± 0·23021				
95% 0·37337 ± 0·17489				
90% 0·37337 ± 0·14678				
Desert scrub				
Relatively intact scrub	71	11·3	66·2	22·5
Degraded scrub	149	12·8	8·1	79·2
Average accuracy	72·7%			
Overall accuracy	75·00%			
Kappa coefficient	0·50093			
S.D.	0·0525			
Confidence level:				
99% 0·50093 ± 0·12695				
95% 0·50093 ± 0·09849				
90% 0·50093 ± 0·08266				

Results of analysis of early- and late-season imagery

The regressions show that overall, the radiance values are not significantly correlated with the field-measured intactness (Figs 6 and 7). The only significant relationship is that of the tobosa sites against the NDVI ratio (Fig. 7). This may be explained by the extensive growth and cover exhibited in this habitat type during the rainy season.

Discussion

TM data is known to be useful for characterizing desert habitat at the site level with extensive field verification. However, the results of this study suggest that TM data has limited value as a rapid assessment tool for automated mapping of even gross categories of intactness in desert habitats at scales ranging from sites, to basins, to entire ecoregions.

Several factors may explain why the variance in habitat intactness is not the dominant influence on the radiative response measured by the satellite. First, vegetation makes a low contribution to the overall reflectance of a given pixel due to low crown cover, small size and number of leaves, and low moisture content of the vegetation itself (Franklin *et al.*, 1993). Therefore, soil features, litter, and shadow become significant components of the radiative response. These factors lead to a reduced relationship between green vegetation indices (NDVI, SAVI, greenness, etc.) and vegetation cover. Second, Chihuahuan soils are often bright, with reflectance in certain bands greater than that of the vegetation present. At the same time, there are extensive areas containing dark and volcanic soils which can have reflectances similar to that of healthy vegetation, particularly in the near-infrared band. Overall, variance in the pixel values is more often attributable to soil and geological features than to vegetation and habitat characteristics.

Third, seasonality is also an important issue, particularly for C_4 dominated communities that exhibit significant seasonal growth and inter-annual variability. Degraded sites may appear spectrally similar to those in senescence, or those experiencing dry seasons or years. The reverse is also true. The dynamic nature of these communities, therefore, has significant implications for single-date mapping of sites, and points to the need for using the most current imagery available.

For these reasons, predicting the relative intactness of large desert areas through a rapid classification of Landsat TM data does not appear to be a cost-effective tool for conservation planning. Perhaps, new applications or advances of remote sensing technologies, or more detailed analyses of relationships among signatures, biodiversity features, and relative intactness, will improve the utility of TM for rapid regional scale conservation planning. Presently, conservation planning efforts may be better served through a combination of visual interpretation of TM scenes for degradation features such as roads and erosion halos around water sources and direct mapping in collaboration with regional experts. This conclusion does not diminish the value of TM data for interpreting habitat types, relative intactness, and change at the level of sites. However, its value is currently limited as a rapid and cost-effective assessment tool for identifying larger blocks of relatively intact desert habitat at the scale of entire basins and ecoregions.

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