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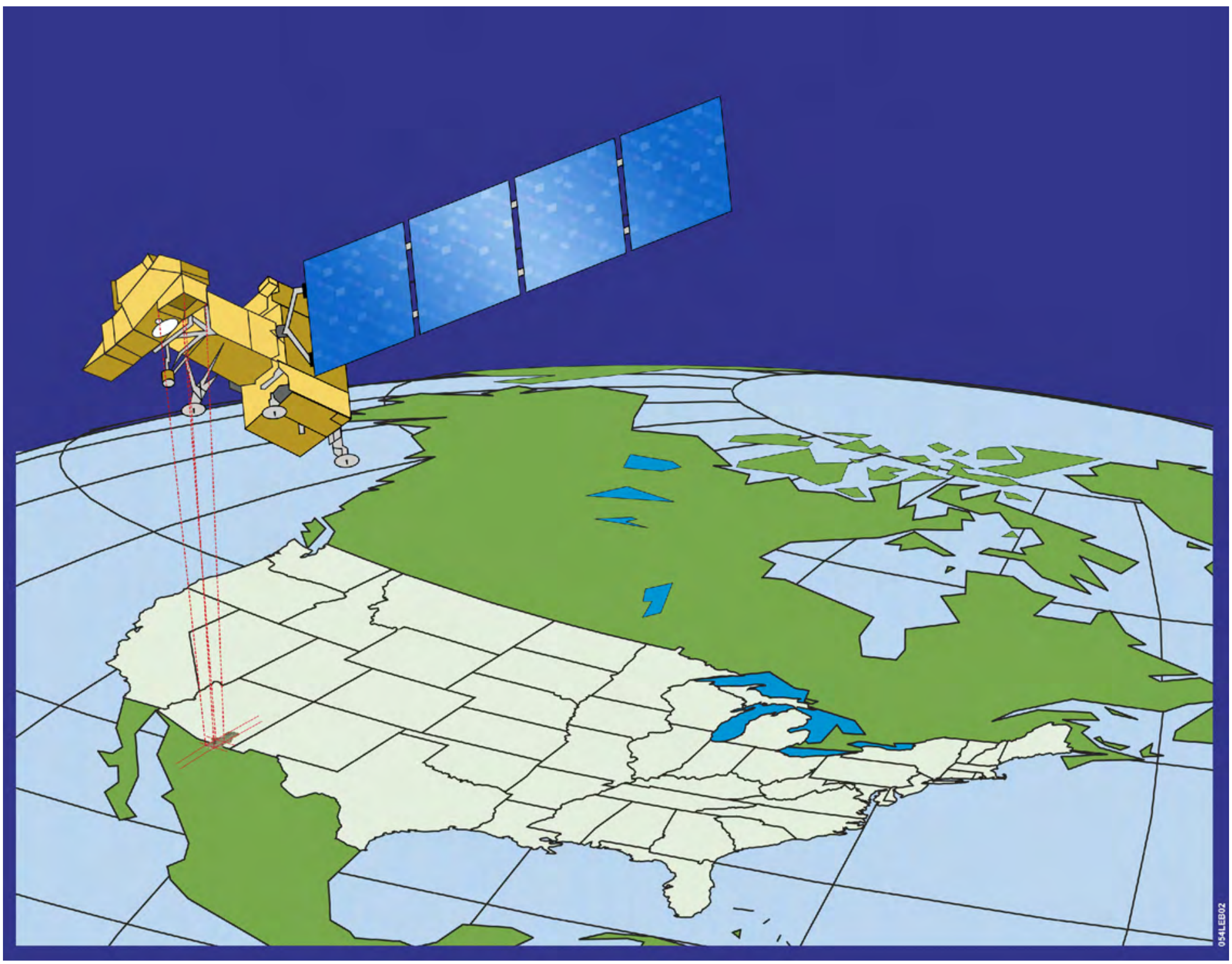
Remote Sensing and Geographic Information Systems for Decision Analysis in Public Resource Administration: A Case Study of 25 Years of Landscape Change in a Southwestern Watershed



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Remote Sensing and Geographic Information Systems for Decision Analysis in Public Resource Administration: A Case Study of 25 Years of Landscape Change in a Southwestern Watershed

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“Siempre beo y es ansi que por la mayor parte quando tenemos entre las manos alguna cosa preciosa y la tratamos sin impedimento no la tenemos ni la preciamos en quanto vale ni entendemos la falta que nos haria si la perdiesemos y por tanto de continuo la bamos teniendo en menos pero despues que la abemos perdido y carecemos del beneficio de ella abemos gran dolor en el coracon y siempre andamos y maginatibos buscando modos y maneras como la tornemos a cobrar....”

“I have always noticed, and it is a fact, that often when we have something valuable in our possession and handle it freely, we do not esteem or appreciate it in all its worth, as we would if we could realize how much we would miss it if we were to lose it. Thus we gradually belittle its value, but once we have lost it and we miss its benefits, we feel it in our heart and are forever wanting, thinking of way and means to retrieve it....”

– *Pedro de Castaneda*
History of the Expedition
October 1596

(A chronicle of Francisco Vasquez de Coronado’s expedition in search of the Seven Cities of Cibola in 1540. It is believed that Coronado’s party followed the San Pedro north from modern-day Sonora into what is now southeastern Arizona.)

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Notice

This report has been peer reviewed by the U.S. Environmental Protection Agency (EPA), through its Office of Research and Development (ORD) and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation by EPA for use.

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Abstract

Alternative futures analysis is a scenario-based approach to regional land planning that attempts to synthesize existing scientific information in a format useful to community decision-makers. Typically, this approach attempts to investigate the impacts of several alternative sets of choices preferred by representative stakeholder groups relative to selected environmental or economical endpoints. Potential impacts from each of the scenarios are compared to current conditions of the region in terms of a set of processes that are modeled within a geographic information system. Future conditions are generally examined from the perspective of a recent baseline condition (versus empirically determined using a series of retrospective measurements).

During the past two decades, important advances in the integration of remote imagery, computer processing, and spatial analysis technologies have been linked to the study of distribution patterns of communities and ecosystems and the ecological processes that affect these patterns. Because of the 25^{+} year availability of commercial satellite imagery, it is possible to examine environmental change and establish models which can narrow the actual choice of possible and probable change scenarios.

This research A) examines the potential to establish reference condition and measure change over large geographic areas; B) determine trends in environmental condition; and C) model and predict future landscape scenarios using advanced space-based technologies. Specifically, landscape pattern measurements were developed from satellite remote sensing, spatial statistics, and geographic information systems technology for a semi-arid watershed in southeast Arizona and northeast Sonora, Mexico and evaluated for their use in a decision-making framework.

Section 1
Introduction

The assessment of land use and land cover is an extremely important activity for contemporary land management. A large body of recent literature (Houghton et al. 1983, Turner 1990, McDonnell and Pickett 1993) suggests that human land-use practices (including type, magnitude, and distribution) are the most important factor influencing natural resource management at local, regional, and global scales.

Traditionally, western U.S. land management has been pursued within small localized areas, such as grazing allotments, or within political jurisdictional boundaries, such as National Park Service units and National Forest systems. Through much of the past century, forests and rangelands have been managed to assure production of timber, livestock, water, minerals, and recreational opportunities, with the primary focus on outputs rather than on the environmental condition left behind.

Today's environmental managers, urban planners, and decision-makers are increasingly expected to examine environmental and economic problems in a larger geographic context to 1) understand the scales at which specific management actions are needed; 2) conceptualize environmental management strategies; 3) formulate sets of alternatives to reduce environmental and economic vulnerability and uncertainty in their evaluation analyses; and 4) to prioritize, conserve, or restore valued natural resources, especially those which provide important economic goods and services.

To manage natural resources effectively, managers and decision-makers need a means to 1) characterize the environment at different hierarchical spatial and temporal scales; 2) identify patterns and processes important at different scales; and 3) compare these patterns and processes to a set of reference conditions (Kaufmann et al. 1994).

A scenario-based approach to regional land planning offers an organizational basis to explore decision analysis and opportunities for public resources. Scenario planning was initially used by the military after the Second World War and since has been tested in a variety of geographical settings to assist stakeholders and policy makers in shaping future use of land and water resources (Schwartz 1996, Steinitz 1990).

Scenario analysis offers several advantages over other assessment frameworks including the ability to intentionally investigate several "futures," i.e. different points of view, at one time. The most important reasons for employing scenario analysis relate primarily to the potential benefits of evaluating all aspects of the local decision-making processes. For example, for land owners interested in protecting their property rights, scenario analysis can be used to understand the range of potential impacts to their lands that may be caused by regional change relative to the type, location, and magnitude of proposed management actions or policy.

Additionally, for elected officials and public administrators, scenarios can be used to test current planning ideas in terms of public perceptions or presumed changes in human demography. Thus scenarios can be used to test the resilience of plans against assumptions about the stability and growth into the future.

Lastly, the use of scenarios also allow members of an entire community to assess the relative impacts of several alternative sets of choices for a desirable future environment. Scenario analysis thus requires that scenarios must be possible, credible, and relevant to be useful in decision-making processes.

The purpose of this research is to develop representative (reference) and change models which can aid in the administration of public natural resources by assessing spatial and temporal changes in land use and land cover at a watershed scale. Subsequently, it is anticipated that through the use of satellite remote sensing and geographic information systems technology that it will be possible to characterize resource stability relative to cumulative environmental stress and model and predict future outcomes based on multi-year trend information.

It is the hypothesis of this project that landscape composition and pattern measures are diagnostic of environmental condition and can be measured using space-based technologies for decision-making processes in public natural resource management. Secondly, it is believed that a set of landscape characteristics measured over time can be established for reporting status and detecting trends in resource vulnerability to human-induced and natural disturbance. Vulnerability for the purpose of this study location has been defined as any serious risk to maintaining a desired state in which community diversity, productivity, and resistance to disturbance are sustained (CEC 1999).

The following sections include a review of pertinent literature relative to 1) performing large-scale environmental assessment and incorporating science into a decision-making process; 2) methodology and materials utilized to remotely measure the environment and analyze very large spatial data sets; 3) demonstration of the combination of technologies to assess changes in a selected location in the semi-arid Southwest, and 4) application of results within a decision-making framework to solve complex problems related to the environment and the people who depend on it.

Section 2

Review of Related Literature

The combination of landscape ecology, advanced technology, and decision analysis provide a unique basis for measuring and interpreting large-scale environmental change. The approach discussed and tested within this report is largely dependent on the integration of natural and social science to interpret landscape pattern metrics relative to specific endpoints such as regional or watershed vulnerability.

2.1 Landscape as an Integration Concept

Landscapes are conceptual units for the study of spatial patterns on the physical environment and the influence of these patterns on important environmental endpoints. Hence, landscapes provide the spatial context for ecosystem dynamics and integrity (O'Neill 1999). Landscape composition and pattern affect key ecological transfer processes which govern the movement or flow of energy, nutrients, water, and biota over time and operate at many scales (Forman and Godron 1986). Hierarchy theory provides the context for integrating multiple scales of information related to the operation of ecological processes (O'Neill et al. 1986). In simple terms, it states that landscapes are organized into patterns within a hierarchy of spatial and temporal scales. Natural and human-induced disturbances occur across a range of spatial and temporal scales and serve to either maintain landscape patterns or initiate phase transitions into new patterns. A landscape framework provides the context 1) to investigate changes in composition, pattern distribution, and process function; 2) to compare conditions across mixed landscapes; and 3) to assess cumulative sources of environmental perturbation (Jensen and Everett 1994).

Land use decisions are generally made at an individual landowner or local scale level, however, the impacts are often manifested cumulatively as change in spatial pattern on the landscape (O'Neill 1988). For example, changes in spatial pattern and composition have been implicated in the decline of biological diversity, ecosystem sustainability, and the ability to recover from disturbance at a number of scales (Flather et al. 1992, O'Neill et al. 1988). This is important because individual land use can result in an additive response condition which impacts ecological processes on a broader scale. In terms of policy, although individual actions occur on a local scale, they are often administratively governed at the greater landscape level of organization, i.e. natural resources are managed by watershed, forest service regions, or within political units such as states and counties.

2.2 Technology and Theory Integration as a Concept for Measuring the Environment

During the past decade, important advances in the integration of remote imagery, computer processing, and spatial analysis technologies have been linked to the study of distribution patterns of communities and ecosystems, ecological processes that affect these patterns, and changes in pattern and process over time. O'Neill et al. 1997 argue that a landscape approach is practical within current technologies for monitoring environmental quality over large regions and it may represent a less expensive approach than using traditional fine-scaled ground-based surveys. Although not all environmental perturbations can be explained or measured via alterations of land cover, this approach at least supplements existing technologies and improves our ability to measure and understand change and trend over time.

Earth observing satellite imagery is globally available via the Advanced Very High Resolution Radiometer (AVHRR). AVHRR imagery (1.1 km^2 pixel resolution) has been used to estimate current vegetation for the United States (Loveland et al. 1991). Improved spectral and spatial resolution imagery is commonly available from commercial and government vendors. It is now clearly possible to map natural resource features at the 60-meter (e.g. Landsat Multi-spectral scanner), 30-meter (Landsat Thematic Mapper) and 10-meter (SPOT) scales of pixel resolution.

2.3 Organizational Framework for Decision Analysis

Landscape architecture involves several areas of theory all of which influence design. Much of the contemporary thinking in regard to landscape design analysis has been outlined in various studies performed by the Harvard University Graduate School of Design (Steinitz 1996, 1993, 1990) in which potential impacts from a number of wide-ranging scenarios are compared to current conditions of a region in terms of a set of processes that are modeled in a geographic information system (GIS). Alternative future landscape analysis involves describing the patterns and significant human and natural processes affecting a geographic area of concern, constructing GIS models to simulate these processes and patterns, creating changes in the landscape by forecasting and by design, and evaluating how the changes affect pattern and process using models. The organizational framework for the analysis identifies six types of question or levels of inquiry (Steinitz 1990).

The six levels of inquiry (and the associated models) are listed below in the order in which they are usually applied (Figure 1):

1. *How should the state of the landscape be described in terms of content, boundaries, space, and time?* (Representation Models)
2. *How does the landscape operate? What are the structural and functional relationships among its elements?* (Process Models)
3. *How does one judge whether the current state of the landscape is working well?* (Evaluation Models)
4. *By what actions might the current representation of the landscape be altered, e.g. by conservation or development?* (Change Models)

    4b. *How might the landscape be changed by current projected trends?* (Projection Models)

    4c. *How might the landscape be changed by designed action?* (Intervention Models)

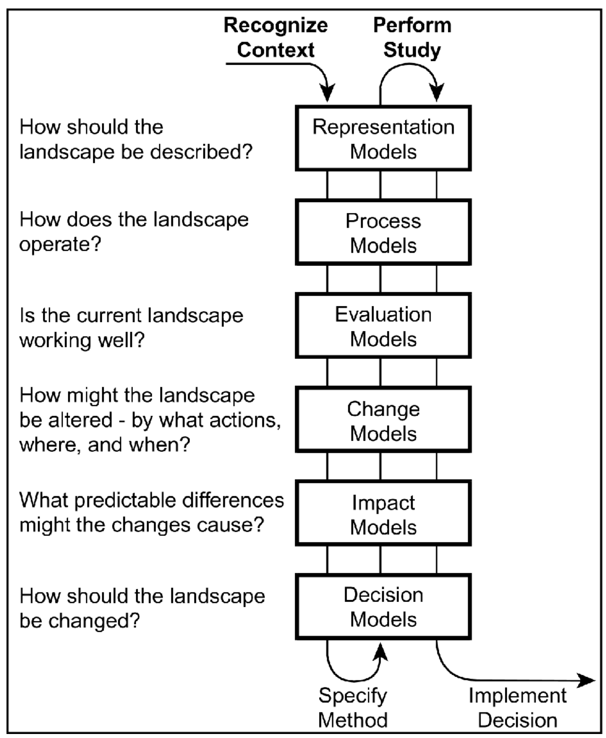

Figure 1. Organizational framework for scenario analysis (Steinitz 1996, 1990).

5. *What predictable differences might the changes cause?* (Impact Models)

6. *How is a decision to change (or conserve) the landscape to be made? How is comparative evaluation to be made among alternative courses of action?* (Decision Models)

In practice, the organizational framework works in reverse, i.e. to be able to decide whether to propose or make a change one needs to know how to compare and evaluate the alternatives. To be able to evaluate the alternatives one needs to predict the comparative impacts from simulated changes. To be able to simulate change, one needs to know what changes to simulate. To be able to consider changes, one needs to evaluate how well the current situation is performing. To be able to evaluate the current situation, one needs to understand how it works. Lastly, to understand how it works, one needs representational information to describe the current state.

The steps outlined above include components which determine the reference (or historic) conditions of the analysis area. Historic reference conditions are useful in managing the environment by telling which processes or functional parts need to be preserved. If only current conditions are the criteria used to make management decisions, there is no basis to determine whether management practices or impacts will lead to environmental outcomes that fall within the historic range of variability (Covington and Moore 1992).

Preferably it is desirable to directly evaluate undisturbed environments to determine reference condition. However, in reality most natural environments have been impacted and modified by both modern and aboriginal humans (Swanson et al. 1993). Secondly, it is much easier to evaluate spatial scales than temporal scales because we can directly observe the present, however, evaluating changes through time is fundamental to predicting potential future conditions.

Historically, it has not been possible to of compare conditions across large landscapes or assess cumulative sources of environmental perturbation. Ideally, historical documents and inventories should provide a significant portion of information for understanding reference condition, however, historical references or reconstructions are generally quite limited (Maser 1990).

As an example, vegetation change in the American West has been a subject of concern throughout the twentieth century (Humphrey 1958, Branson 1985, Grover and Musick 1990, Bahre 1991, and Bahre and Shelton 1993). The information for vegetation change has largely been derived from archival literature and photography. Most of the evidence for vegetation change is actually provided from a series of matched photographs beginning in the late 1800s and early 1900s (Figure 2). However, there are serious drawbacks in using this technique to assign change over this period of history.

As some authors (Bahre 1991) point out, the field of view in ground photographs is usually oblique and covers little total area which limits their usefulness in determining change in plant occurrence over large regional areas. Secondly, the historic photographic series are usually separated by large periods of time and they are often captured more than a decade after the sites were first disturbed by human activity. Lastly, the change photography has largely been used for qualitative comparisons and little progress has been made in quantifying and characterizing vegetation change, especially in regard to determining which systems are most resilient or vulnerable. Although several studies have addressed specific aspects of vegetation change in the Southwest, few have attempted to synthesize the cumulative impacts over large regional or watershed areas.

Important advances in the integration of remote imagery, computer processing, and spatial analysis technologies have been coupled to landscape ecology theory to study the distribution patterns of communities and ecosystems, human and environmental processes that affect these patterns, and changes in pattern and process over time. The work provided from this research is intended to contribute to our ability to characterize large assessment areas (representative model) and provide predictive inference (change model) for alternative future scenarios which can lead to a comparative analysis of impacts relative to alternative courses of management action (decision model).

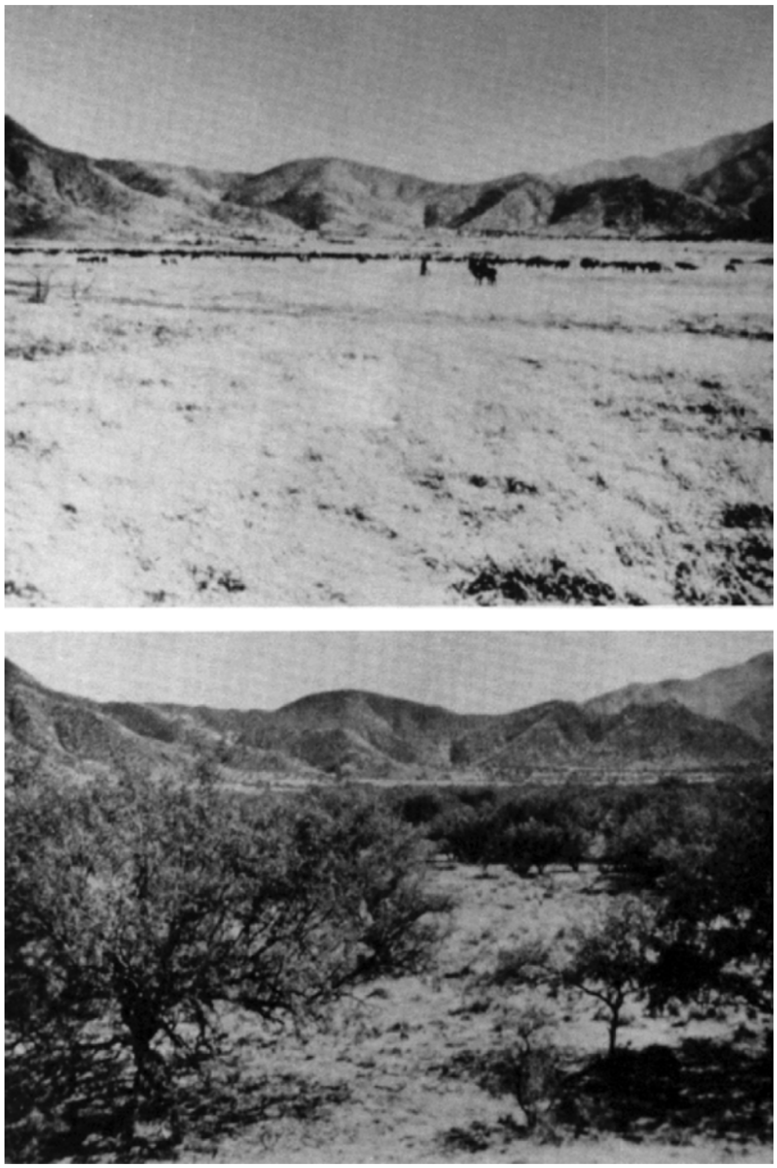

Figure 2. Landscape change from perennial grassland to mesquite woodland in a semi-arid rangeland, (Santa Rita Mountains, Arizona). Top photo (1903); bottom photo (1941).

Section 3

Materials and Methods

The application of several advanced technologies to assess spatial and temporal changes was tested in a moderately sized Southwestern watershed described below. The source data were drawn off a series of Landsat satellite platforms beginning in 1973. The case study area was selected for a variety of reasons including data richness, circumstantial information related to change, and stakeholder involvement. It represents one of the first attempts to examine large scale change over a quarter century of time using large datasets acquired from remote earth-orbiting sensors.

3.1 Study Site

The study location is the upper San Pedro River basin which originates in Sonora, Mexico and flows north into southeastern Arizona (Figure 3). The San Pedro River is an international basin with significantly different cross border legal and land use practices (CEC 1998, USBLM 1998, Tellman et al. 1997). The watershed embodies a variety of characteristics which make it an exceptional outdoor laboratory for addressing a large number of scientific questions in arid and semi-arid hydrology, ecology, meteorology, and the social and policy sciences. The Upper San Pedro Watershed represents a transition area between the Sonoran and Chihuahuan deserts and topography, climate, and vegetation vary substantially across the watershed. Elevation ranges from 900 - 2,900 m and annual rainfall ranges from 300 to 750 mm. Biome types include desertscrub, grasslands, oak woodland-savannah, mesquite woodland, riparian forest, coniferous forest, and agriculture. The upper watershed encompasses an area of approximately 7,600 km^2 (5,800 km^2 in Arizona and 1,800 km^2 in Sonora, Mexico).

3.2 Image Acquisition and Characterization

Remote imagery was derived from the Landsat Multi-spectral Scanner (MSS) and Landsat Thematic Mapper (TM) earth observing satellites (path/row 35/38 and 35/39). Landsat-MSS satellite scenes were selected from the North American Landscape Characterization (NALC) project (USEPA 1993). The scenes available in the NALC database (1973-92) and Landsat TM (1997) are from four pre-monsoon dates for a period of approximately 25 years (i.e. 5 June 1973, 10 June 1986, 2 June 1992, 8 June 1997). All imagery in the database is coregistered and georeferenced to a 60 x 60 meter Universal Transverse Mercator (UTM) ground coordinate grid with a nominal geometric precision of 1-1.5 pixels (60-90 m). Digital land cover maps were developed separately for each year using 10 classes: Forest, Oak Woodland, Mesquite Woodland, Grassland, Desertscrub, Riparian, Agriculture, Urban, Water, and Barren (Figure 4). The cover classes are briefly described in Table 1. A decision similar to other studies (Klemas et al. 1993) was made to classify the images separately prior to change detection analysis because of the difficulty in normalizing images derived from different satellite sensors. The landscape changes were analyzed in a geographical information system using ARC/INFO software.

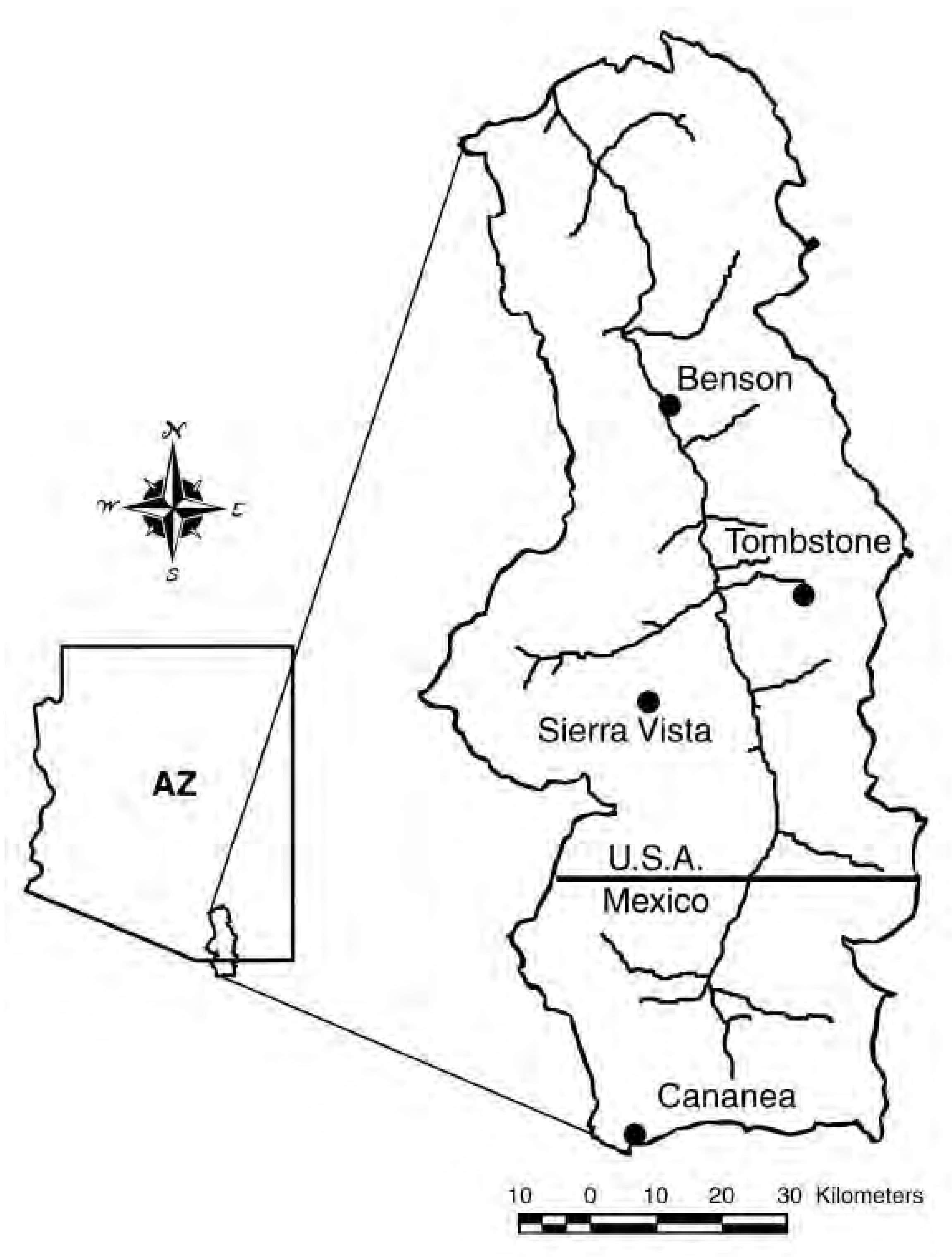

Figure 3. Location of the Upper San Pedro River Basin, Arizona/Sonora.

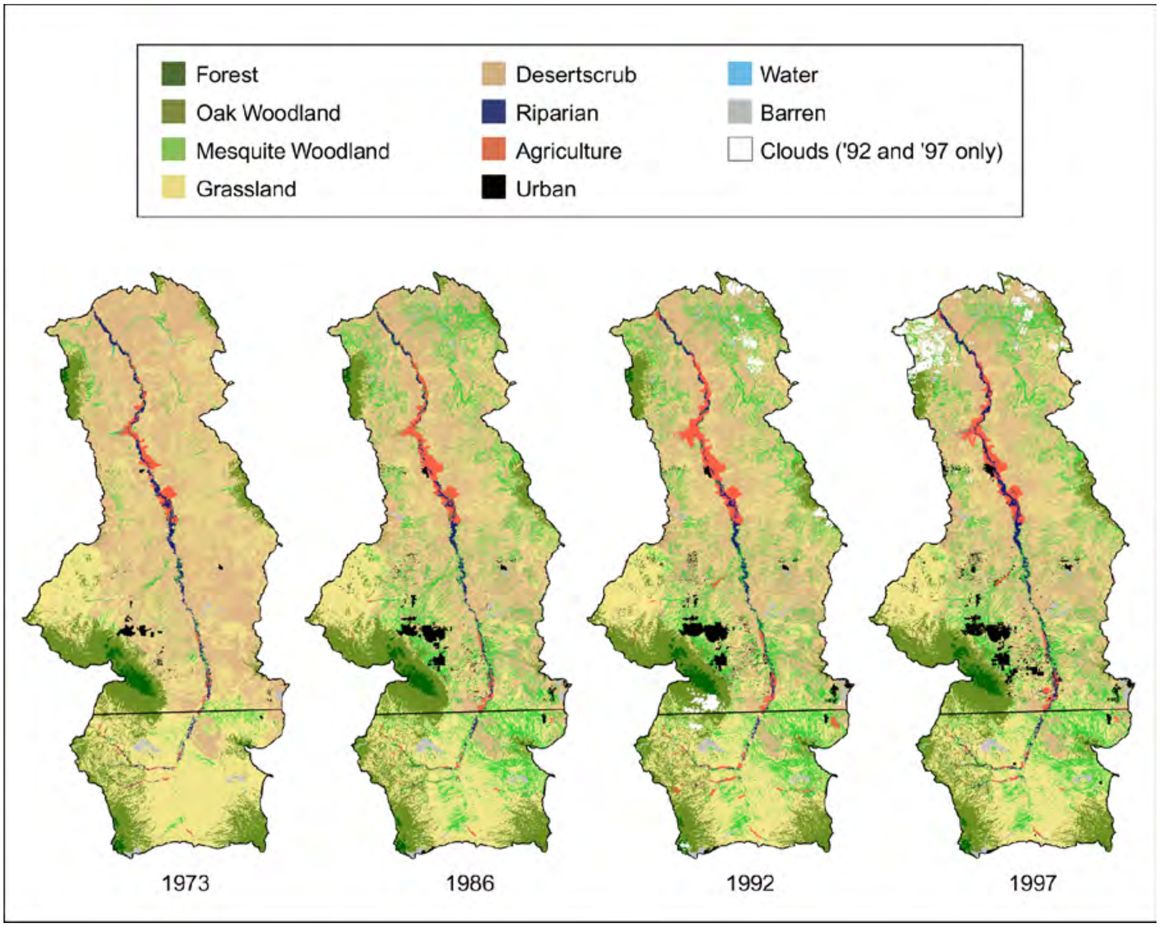

Figure 4. Land cover in the Upper San Pedro Watershed (U.S./Mexico). Source: Landsat MSS (5 June 1973, 10 June 1986, 2 June 1992) and Landsat TM (8 June 1997).

The first step in the image classification was using ERDAS IMAGINE 8.3 software procedure ISODATA to perform an unsupervised classification using bands 1 (green), 2 (red) and 4 (near infrared) to produce a map with 60 spectrally distinct classes. The choice of 60 classes was based on previous experience with NALC data and usually gave satisfactory trade-off between the total number of classes and the number of mixed classes. In this context, it proved helpful to define a larger set of 21 intermediate classes, which were easier to relate to the spectral information. For example, the Barren class contains bare rock, chalk deposits, mines, tailing ponds, etc. which have very different spectral signatures. Each class was then displayed over the false-color image and classes were assigned into one of the 21 land cover categories or as mixed. The software allows the interactive manipulation of the signatures for each class which allowed many of the mixed classes to be resolved.

The remaining mixed classes were separated into different categories using a variety of ancillary information sources, such as the topographic maps (scale 1:50,000) produced by INEGI, the Mexican National Institute of Statistics, Geography and Information, and by the U.S. Geological Survey (scale 1:24,000). The land use information used varied depending on the image being analyzed. Thus the classification of the 1997 image relied heavily on field visits to establish ground control. Five 3-day site visits were carried out from September 1997 to June 1998 to collect specific land cover data with the aid of Global Positioning System equipment which were incorporated into successive iterations of the classification process.

Table 1. Land cover class descriptions for the Upper San Pedro Watershed.

Forest	Vegetative communities comprised principally of trees potentially over 10 m in height and frequently characterized by closed or multi-layered canopies. Species in this category are evergreen (with the exception of aspen), largely coniferous (e.g. ponderosa pine), and restricted to the upper elevations of mountains that arise off the desert floor.
Oak Woodland	Vegetative communities dominated by evergreen trees (*Quercus spp.*) with a mean height usually between 6 and 15 m. Tree canopy is usually open or interrupted and singularly layered. This cover type often grades into forests at its upper boundary and into semi-arid grassland below.
Mesquite Woodland	Vegetative communities dominated by leguminous trees whose crowns cover 15% or more of the ground often resulting in dense thickets. Historically maintained maximum development on alluvium of old dissected flood plains; now present without proximity to major watercourses. Winter deciduous and generally found at elevations below 1,200 m.
Grassland	Vegetative communities dominated by perennial and annual grasses with occasional herbaceous species present. Generally grass height is under 1 m and they occur at elevations between 1,100 and 1,700 m; sometimes as high as 1,900 m. This is a landscape largely dominated by perennial bunch grasses separated by intervening bare ground or low-growing sod grasses and annual grasses with a less-interrupted canopy. Semi-arid grasslands are mostly positioned in elevation between evergreen woodland above and desertscrub below.
Desertscrub	Vegetative communities comprised of short shrubs with sparse foliage and small cacti that occur between 700 and 1,500 m in elevation. Within the San Pedro river basin this community is often dominated by one of at least three species, i.e. creosotebush, tarbush, and whitethorn acacia. Individual plants are often separated by significant areas of barren ground devoid of perennial vegetation. Many desertscrub species are drought-deciduous.
Riparian	Vegetative communities adjacent to perennial and intermittent stream reaches. Trees can potentially exceed an overstory height of 10 m and are frequently characterized by closed or multi-layered canopies depending on regeneration. Species within the San Pedro basin are largely dominated by two species, i.e. cottonwood and Goodding willow. Riparian species are largely winter deciduous.
Agriculture	Crops actively cultivated (and irrigated). In the San Pedro River basin these are primarily found along the upper terraces of the riparian corridor and are dominated by hay and alfalfa. They are minimally represented in overall extent (less than 2%) within the basin and are irrigated by ground and pivot-sprinkler systems.
Urban (Low and High Density)	This is a land cover dominated by small ejidos (farming villages or communes), retirement homes, or residential neighborhoods (Sierra Vista). Heavy industry is represented by a single open-pit copper mining district near the headwaters of the San Pedro River near Cananea, Sonora (Mexico).
Water	Sparse free-standing water is available in the watershed. This category would be mostly represented by perennial reaches of the San Pedro and Babocomari rivers with some attached pools or repressos (earthen reservoirs), tailings ponds near Cananea, ponds near recreational sites such as parks and golf courses, and sewage treatment ponds east of the city of Sierra Vista, Arizona.
Barren	A cover class represented by large rock outcropping or active and abandoned mines (including tailings) that are largely absent of above-ground vegetation.

3.3 Change Detection Analysis

Mouat et al. (1993) review remote sensing techniques for detecting change by analyzing multi-date imagery. The San Pedro digital land cover maps were transferred into UTM map projection coordinates and incorporated into a geographical information system for change analysis. Change was analyzed using landscape statistical software to produce landscape statistics, including actual total extent. Image enhancement in ARC/INFO allows mathematical treatment of the composite images and to display change, either as gain, loss, or no change. This technique has been very useful in identifying semi-arid areas which have undergone change relative to human-induced and natural environmental stress (Pillon et al. 1988) and was employed for this research.

Landsat-MSS 1973 was used for the baseline condition. Change between time intervals, i.e. 1973, 1986, 1992, and 1997 was measured and the discrete landscape metrics were described (Table 2). Landscape statistics that describe shape and size were used to assess dominance, fragmentation, and rates of conversion in an effort to determine sensitive measures for resistance to change (= landscape resilience). Sample size was 2,100,407 pixels (60-m resolution) per digital image map.

Table 2. Landscape change statistics.

Statistic	Description
Dominance	Area-based metric which indicates the extent to which the landscape is dominated by a single land cover type.
Connectivity	Percentage of edges that are of the same land cover class. Higher value indicates lower patchiness. Only calculated for individual land cover classes.
Total # of patches	Number of polygons of a single land cover type.
Largest patch size	The size of the largest contiguous polygon of a single land cover type.
Avg. Patch size	Average patch size. Overall average is not area weighted.

Results

Results for land cover extent (total hectares and percent by class) by sample year and relative change for each interval period are presented in Tables 3 and 4. Results vary over the 25-year period, however, certain land cover types, i.e. forest and oak woodland have changed little over this period relative to other classes.

Table 3. Proportional land cover extent as total hectares and percent for the Upper San Pedro Watershed (1973, 1986, 1992, and 1997).

	1973		1986		1992		1997	
	Hectares	**%**	**Hectares**	**%**	**Hectares**	**%**	**Hectares**	**%**
Forest	7446	0.98	7437	0.98	7045	0.93	7071	0.94
Oak Woodland	93612	12.38	93464	12.36	88894	11.76	90270	11.94
Mesquite	20821	2.75	106968	14.15	105192	13.91	101602	13.44
Grassland	312850	41.37	267321	35.35	265231	35.08	263432	34.84
Desertscrub	296330	39.19	243502	32.20	235480	31.14	229953	30.41
Riparian	8665	1.15	8852	1.17	8889	1.18	9218	1.22
Agriculture	8775	1.16	11507	1.52	14859	1.97	14530	1.92
Urban	3205	0.42	10002	1.32	12574	1.66	16494	2.18
Water	264	0.03	294	0.04	337	0.04	415	0.05
Barren	4177	0.55	6799	0.90	6792	0.90	6769	0.90
Clouds	0	0.00	0	0.00	10850	1.44	16388	2.17

Table 4. Percent relative land cover change for the Upper San Pedro Watershed (1973-1986, 1986-1992, 1992-1997, and 1973-1997).

	1973-1986	1986-1992	1992-1997	1973-1997
Forest	-0.12	-5.27	0.37	-5.04
Oak Woodland	-0.16	-4.89	1.55	-3.57
Mesquite	413.75	-1.66	-3.41	387.98
Grassland	-14.55	-0.78	-0.68	-15.80
Desertscrub	-17.83	-3.29	-2.35	-22.40
Riparian	2.16	0.42	3.70	6.38
Agriculture	31.13	29.13	-2.21	65.58
Urban	212.07	25.71	31.18	414.63
Water	11.36	14.63	23.15	57.20
Barren	62.77	-0.10	-0.34	62.05

Five of the ten land cover types represent rare (<2% total extent) classes in the study area. Although urban land cover represents close to 2 per cent of the land cover, growth of this cover type, particularly in Arizona, has been rapid and has increased from 3,205 total ha in 1973 to 16,494 ha in 1997; a relative increase of 415 percent for this period (Table 4). The major surge in urbanization occurred within the first 13-year period from 1973-1986 when urban cover increased three times from the 1973 baseline (Figure 5).

Mesquite woodland, a native tree life-form, has encroached upon the entire watershed. Mesquite total extent increased five-fold between 1973 and 1986 from 20,821 to 106,968 ha (Table 3, Figure 6). The baseline extent of mesquite for the watershed in 1973 was 2.75 percent and by 1997 it represented 13.44 percent of the total land cover.

Major decreasing cover types included desertscrub and grassland. Although grassland dominates the San Pedro landscape for each of the four sample periods, its total extent has steadily declined. Almost 50,000 ha of perennial and annual grasses were lost between 1973 and 1997. The major decrease for this cover type occurred between 1973 and 1986 (45,529 ha lost) whereas 2,090 ha and 1,799 ha were lost the following periods between 1986-1992 and 1992-1997, respectively (Figure 7).

Desertscrub had an identical trend as grasslands. Desertscrub (Sonoran and Chihuahuan species) represents the second most dominant land cover type within the study area. Over 66,000 ha of desertscrub were lost over the 25-year period. Similar to grasslands, most of this loss (80 percent) occurred during the first 13 years between 1973 and 1986 (Figure 8).

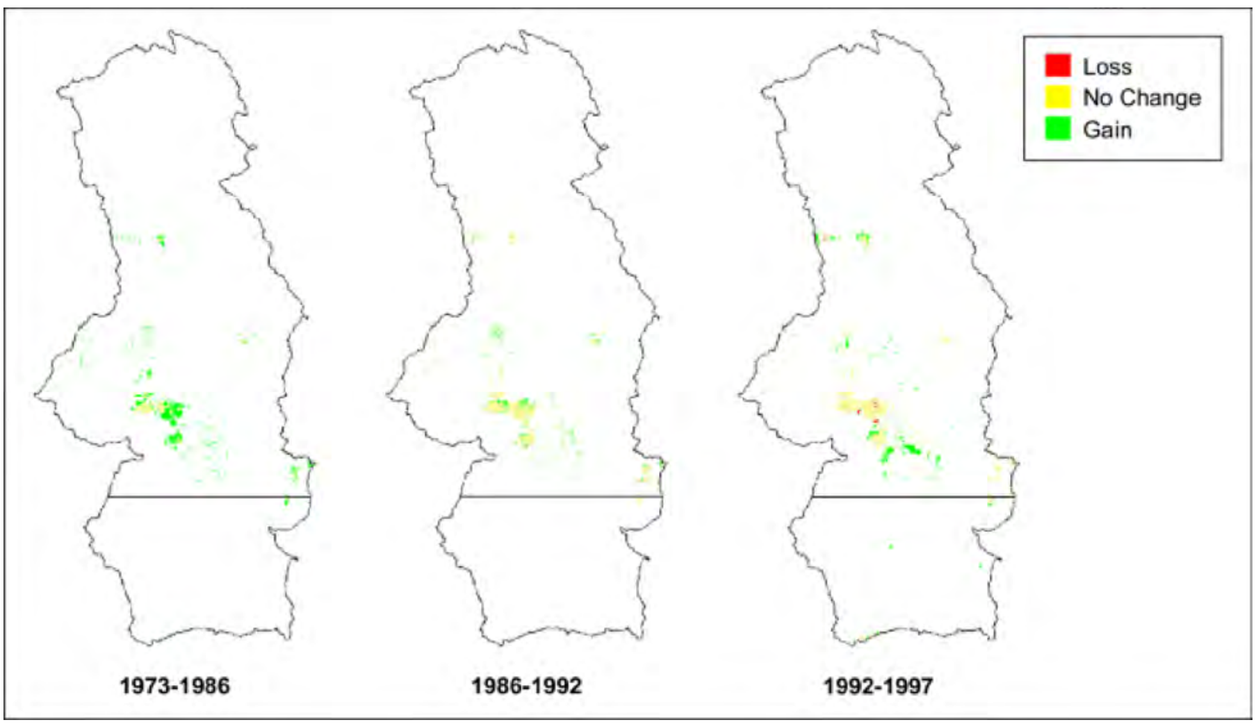

Figure 5. Urban land cover change for the Upper San Pedro Watershed (1973-1986, 1986-1992, and 1992-1997).

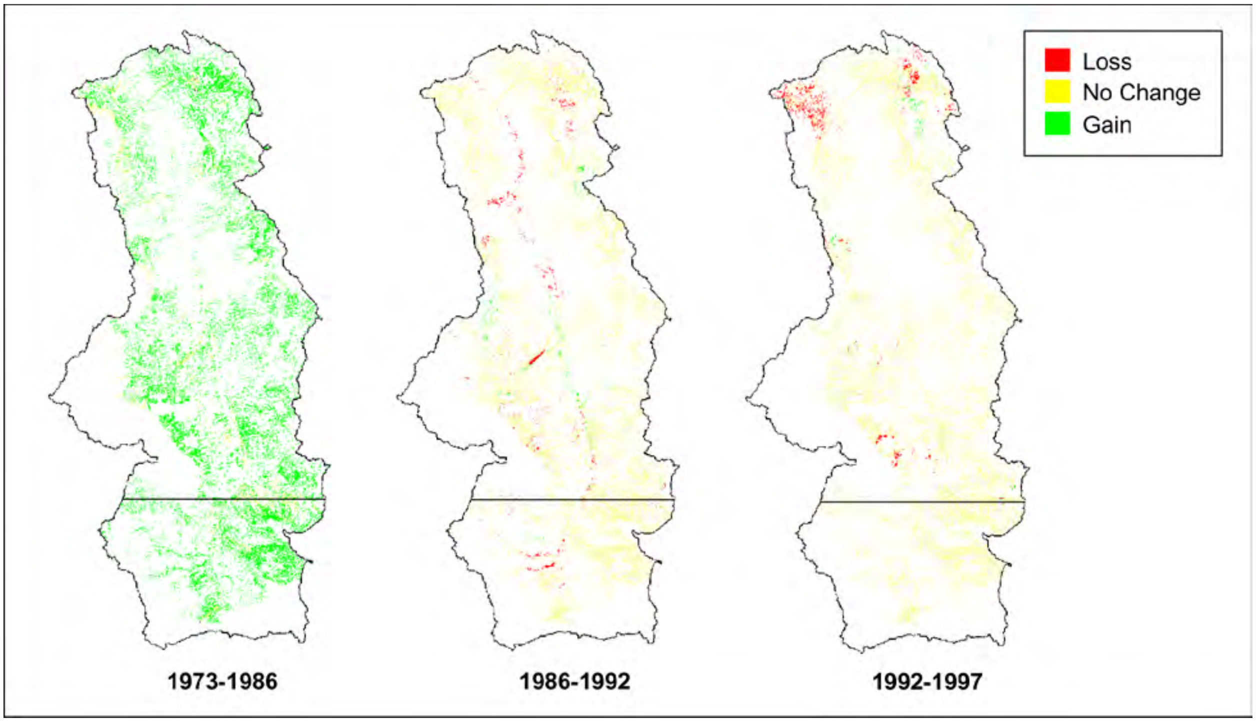

Figure 6. Mesquite land cover change for the Upper San Pedro Watershed (1973-1986, 1986-1992, and 1992-1997).

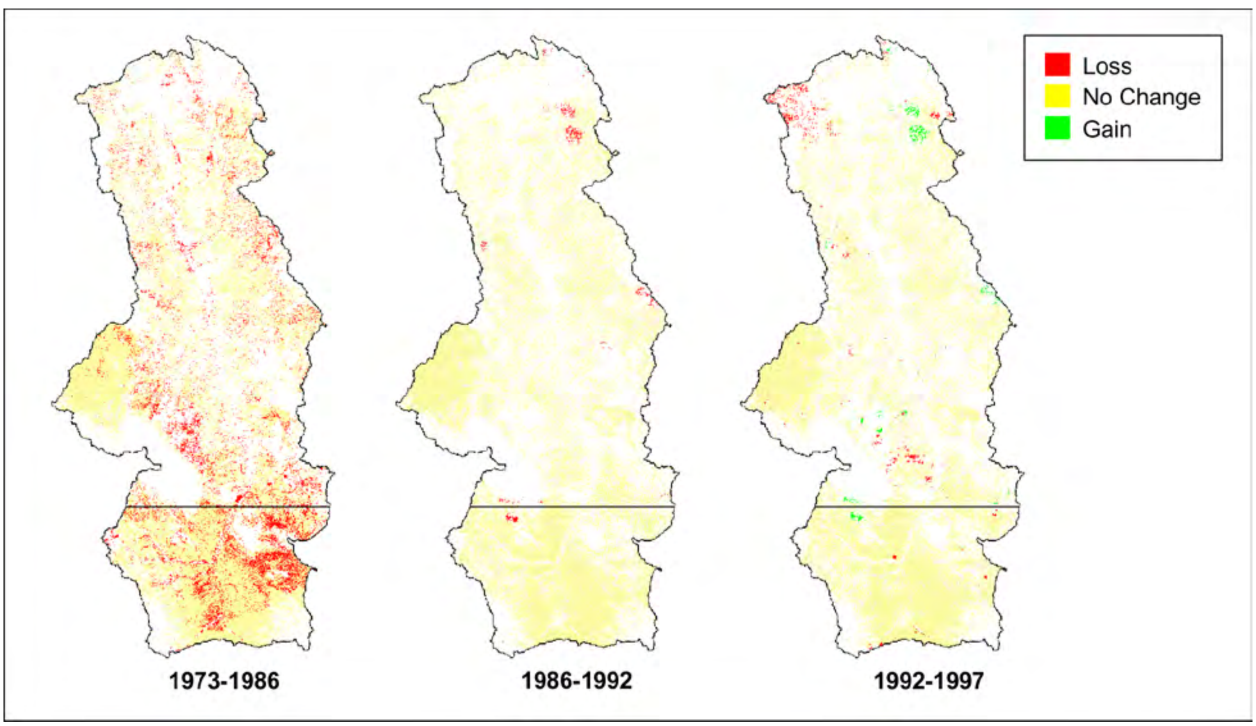

Figure 7. Grassland land cover change for the Upper San Pedro Watershed (1973-1986, 1986-1992, and 1992-1997).

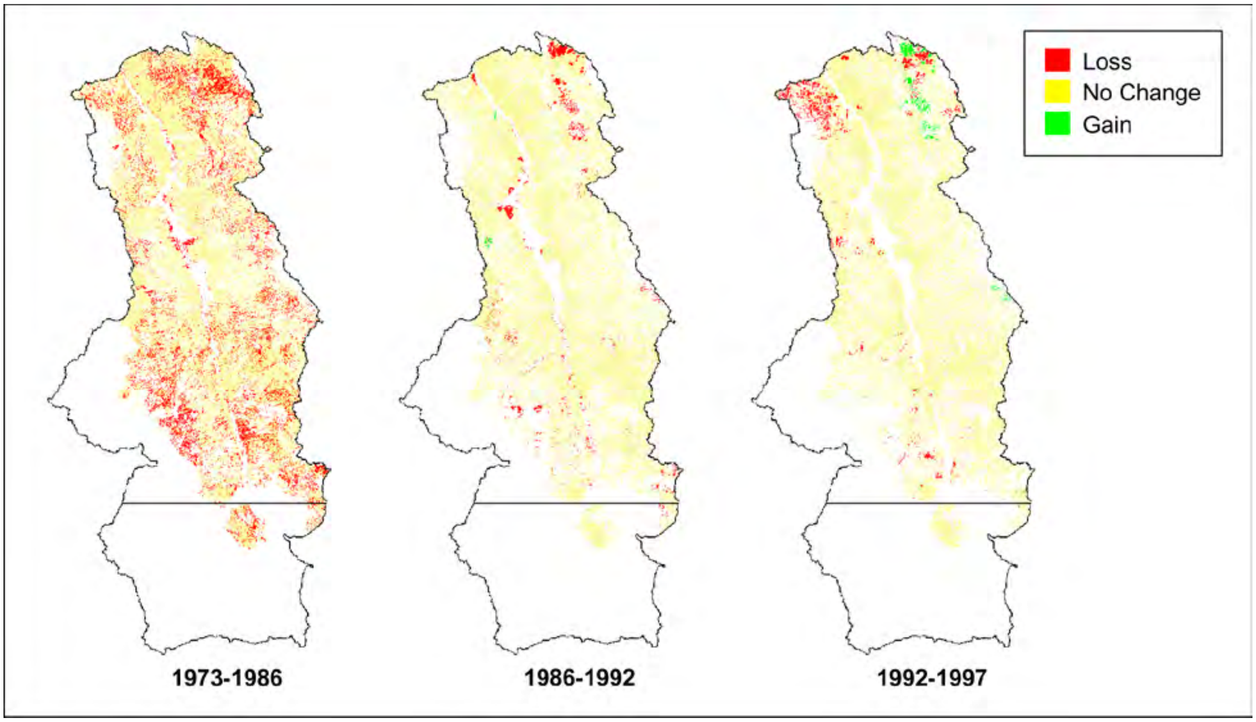

Figure 8. Desertscrub land cover change for the Upper San Pedro Watershed (1973-1986, 1986-1992, and 1992-1997).

Landscape statistics that describe shape and size were used to assess dominance, fragmentation, and conversion matrices for selected cover types and are presented in Table 5.

Table 5. Landscape change statistics for four land cover classes in the Upper San Pedro Watershed (1973-1997).

	Grassland			**Desertscrub**			**Mesquite Woodland**			**Urban**		
	1973	**1997**	% Rel. Change	**1973**	**1997**	% Rel. Change	**1973**	**1997**	% Rel. Change	**1973**	**1997**	% Rel. Change
Area (ha)	312,850	263,432	-15.80	296,330	229,953	-22.40	20,821	101,602	+387.98	3,205	16,494	+414.63
% Cover	41.37	34.84	-15.80	39.19	30.41	-22.40	2.75	13.44	+387.98	0.42	2.18	+414.63
# of Patches	50,715	58,142	+14.64	26,260	39,991	+52.29	15,558	53,310	+242.65	418	3,010	+620.10
Largest Patch (ha)	126,258	53,173	-57.89	201,165	37,361	-81.43	461.52	3,574	+674.34	982	4,938	+402.82
Ave Patch Size	6.18	4.54	-26.54	11.3	5.76	-49.03	1.34	1.91	+42.54	7.86	5.55	-29.39
Connectivity	0.62	0.56	-9.68	0.66	0.55	-16.67	0.31	0.37	+19.35	0.74	0.69	-6.76

Mesquite woodland has experienced the most rapid increase in extent during the study period. More than 80,000 ha of mesquite were gained since the 1973 baseline and it has undergone expansion by aggregation to form clusters which later coalesced into large woodland patches. The number of mesquite polygons (patches) and average patch size have increased steadily throughout the study area (Table 5). Mesquite patches have increased up to 3,574 ha in size and increasingly become more connected, i.e. the percentage of edges are of identical land cover class, resulting in large stands with closed canopies.

Urban cover has also increased during the study period. Similar to mesquite, urban cover has increased in the number of patches and largest patch size from 418 and 982 ha to 3010 and 4,938 ha, respectively. However, average urban patch size and connectivity have actually decreased, likely due to urbanization of the outlying suburban areas.

The majority of mesquite and urban gain during the 25-year study period were predominantly derived from desertscrub and grassland cover classes. Subsequently, desertscrub and grassland show a general trend in fragmentation and actual loss. Total extent for these two cover classes decreases through time and the number of patches increases. Additionally, the average patch size for desertscrub and grassland decreases from 11.3 to 5.76 ha and 6.18 to 4.54 ha, respectively and connectivity decreases from the 1973 baseline (Table 5).

Conclusions

The methods developed as an outcome of this study have been employed for their capability to assess the spatial and temporal changes in land use and land cover at a landscape scale and to subsequently determine an effective means to measure landscape stability over large assessment areas such as watersheds. The ability to interpret condition and change over large areas has only become feasible with the availability of remotely sensed data such as Landsat. The advantages of this new approach make it possible to 1) observe large geographic areas and multi-jurisdictions in their entirety; 2) quantify landscape pattern and the areal extent of resources; 3) observe changes and trend in large-scale patterns through time; and to 4) assess cumulative sources of environmental perturbation (Graham et al. 1991, Urban et al. 1987).

Specifically, remote sensing integrated into a GIS environment provides an ability to characterize large assessment areas and establish reference condition. The use of landscape metrics based on land cover generated from remote sensors provides a unique opportunity to assess areas of large regional scale. In terms of the alternative landscape analysis it fulfills the need to describe the landscape in terms of content, boundaries, space, and time and thus provides the representative model for the initial step of scenario analysis.

Secondly, the results of this research will benefit decision-makers and natural resource managers who are principally interested in evaluating present and past cumulative impacts to a watershed or formulating alternative management strategies to sustain environmental health and economical viability into the future. The pattern measurements from this research provide predictive inference (a change model) for measuring and evaluating change. Thus it serves to answer questions related to how might the landscape be changed by current projected trends (Figure 9).

Lastly, the combination of remote sensing, GIS, and landscape pattern metrics help contribute to the comparative evaluation to be made among alternative courses of management and policy action (i.e. alternative future scenarios) which ultimately lead to the decision model (Steinitz et al. 2000).

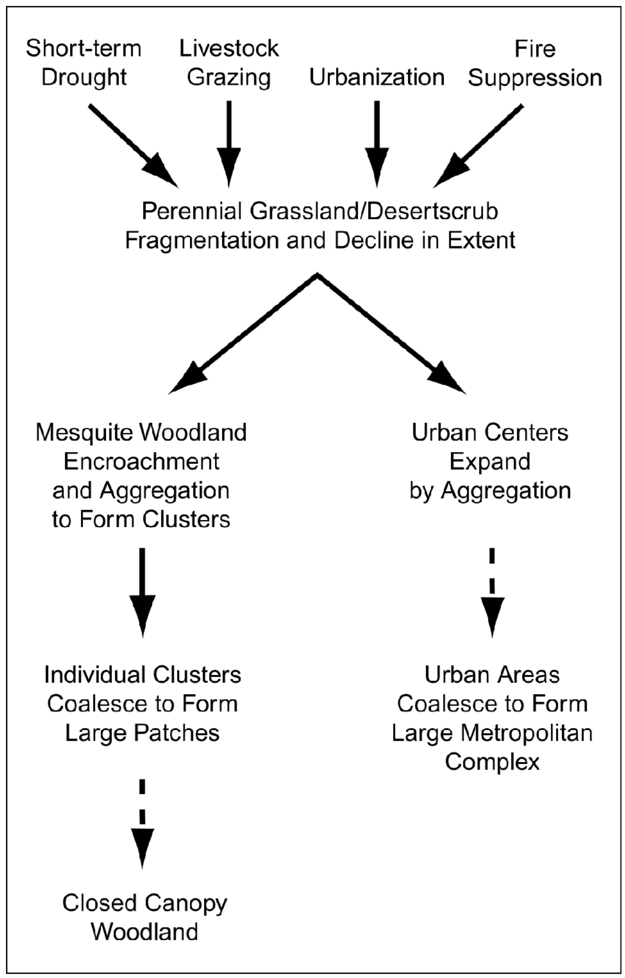

Figure 9. Conceptual model of vegetation phase transitions in a semi-arid watershed.

The principal degradation processes that have occurred throughout the western rangelands involves 1) changes of vegetative cover, i.e. decrease in above ground productivity and compositional diversity (primarily manifested by the introduction of exotic annual species or native woody xerophytic shrubs and trees) and 2) acceleration of water and wind erosion processes. Historically, these have been linked to both human-induced and natural stressors, i.e. livestock grazing and short-term drought (Grover and Musick 1990). However, rapid urbanization in the arid and semi-arid Southwest, within the last 25 years has become an important factor in altering land cover composition and pattern. The purpose of this research was not to determine cause and effect, however, clearly native grassland and desertscrub communities in the upper San Pedro River basin are rapidly declining in the wake of major phase transformation into mesquite woodland and a newly urbanized environment (Figure 9).

Collectively, the combination of new technologies with an organizational framework for decision analysis provides decision-makers with an improved ability to understand the conditions of current and past environment and provides a better predictor for consequences of future actions.

In the specific example of the Upper San Pedro River (Arizona/Sonora), the area has been recognized by the U.S. Congress and under international treaty as a site important to the conservation of North American riparian vegetation and migratory birds (CEC 1999). Much of the current public discourse relates to policy for preserving the transboundary wildlife species connected to the presumably imperiled riparian corridor. The riparian habitat, although containing important resource values, represents only 1.22 per cent of the total land cover and the U.S. portion is protected by National Conservation Area status. Although this cover type is considered the most vulnerable within the watershed, the landscape analysis indicates that upland land cover types, i.e. grassland and desertscrub, are fast disappearing as a result of urban development and conversion to mesquite woodland. Hence, this work offers a different perspective to natural resource managers and policy makers whom are concerned with the preservation of biological diversity and sustainability for present and future generations.

Future research should explore the application of integrated technologies to assess environmental condition in other geographies and the integration of science results into a decision analysis framework. The primary spatial datasets can be made readily available to decision-makers and landscape assessment tools could be developed to assist in the interpretation of results within a natural resource and urban planning process.

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