USING GIS AND REMOTE SENSING TECHNIQUES TO ESTIMATE LAND COVER CHANGES IN A DESERT WATERSHED

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Geographic information systems (GIS) and remote sensing techniques are powerful tools in the analysis of temporal changes in land cover or land use. Land cover refers to the type of feature present on the surface of the earth, including vegetation and nonvegetation features. Urban buildings, lakes, dense forests, and glacial ice are all examples of land cover types. Land use describes the human activity associated with a specific part of land and usually emphasizes the functional role of that land for economic activities (Lillesand 1987; Campbell 1987). Changes occurring in land cover and land use can generally be attributed to either natural or anthropogenic forces. Natural changes include both seasonal and annual variations in climatic conditions, and are often reflected by variations in natural land cover; fire can also induce natural changes. Changes resulting from anthropogenic forces are the result of human modification of the environment (Pilon et al. 1988). It is important to mention that the overall land use classes may change little over long periods of time, but the impact on wildlife populations and other components of affected ecosystems can be quite significant (Green 1994). GIS and remote sensing techniques can compare spatial information from two or more time intervals more readily than non-computer-based methods. Since the earliest Landsat imagery appeared in 1972, paired images from subsequent dates have been used to detect land cover and land use changes in the landscape (Iverson and Risser 1987).

Land use patterns in the study area, which is in the Sonoyta River watershed, are changing in both nature and intensity. Agricultural expansion has increased from 2,168 hectares in 1978 to nearly 10,000 hectares in 1987, and the population of Sonoyta has increased in the same period from less than 10,000 to more than 15,000 (Bennett and Kunzmann 1987). This growth suggests that the demand for urban and agricultural water will continue to expand. The exploitation of the underground water table in the Sonoyta River watershed and the expansion of agricultural activities in this region are presenting a serious threat to the wildlife and vegetation that are dependent on the soil and water resources of this watershed. Thus, these anthropogenic activities affect the biotic resources of different ecosystems included in and/or adjacent to important biological reserves such as EL Pinacate National Park in Mexico, Organ Pipe Cactus National Monument (ORPI), and the Cabeza Prieta National Wildlife Refuge in the U.S.

Brown et al. (1983) did an inventory of surface water resources at ORPI and found that gains in surface water sources have occurred due to the creation of many artificial water sources, including stock tanks, sewage disposal ponds, and wells with their attendant watering troughs. However, important losses of water sources have also occurred. Reviewing historical information, they found that in the early 1930s there were permanent *cienegas* (marshes) located along the Sonoyta River just south of the monument, which indicates that there was an important source of underground water in the watershed to support surface water bodies. Thus, they concluded that "the current pumping of ground water for agricultural purposes has further lowered the water table. As a consequence, the Sonoyta River today is a greatly depleted remnant of the surface water resource it once was. Historically, the flow from the warm springs at Quitovaquito had a surface connection with the Sonoyta River; this is no longer the case." Carruth (1994) reports a water level decline in the Quitovaquito Springs area caused by pumping near the Rio Sonoyta, Mexico.

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Therefore, considering that a better understanding of changes in historical land use should provide additional knowledge about conditions in the watershed, the principal objective of this study was to estimate the land cover and land use changes that occurred in an area located in the Sonoyta River watershed between 1972 and 1992 using remote sensing and GIS techniques.

Methods

The 8595 km^2 study area is located in the northwestern part of Sonora, Mexico and southwestern Arizona between north latitudes 31° 22' 55.3" and 32° 05' 49.5", and west longitudes 112° 09' 30.5" and 113° 18' 58.3" (Figure 1). Its climate is dry with a mean annual temperature of 21.4°C, maximum temperature of 45.1°C, and minimum temperature of -3.3°C. The mean annual precipitation is 209.7 mm (SARH 1994).

Detection of change in land use class areas was accomplished using Landsat MSS data processed with the remote sensing program ERDAS version 7.5, produced by Erdas, Inc., and the IDRISI GIS program version 4.1 developed by Clark University, Massachusetts. The scenes used in this study were acquired from the EROS Data Center of the U.S. Geological Survey in Sioux Falls, SD. The scenes are dated from September of 1972 and October 1992. The subsets defining the 1972 and 1992 study areas were extracted from the original scenes using the ERDAS program and the satellite imagery processing equipment available in the Remote Sensing Center, Office of Arid Lands Studies, University of Arizona.

After geometric and atmospheric correction, the 1972 and 1992 images were geographically registered. The identical geographic coordinates

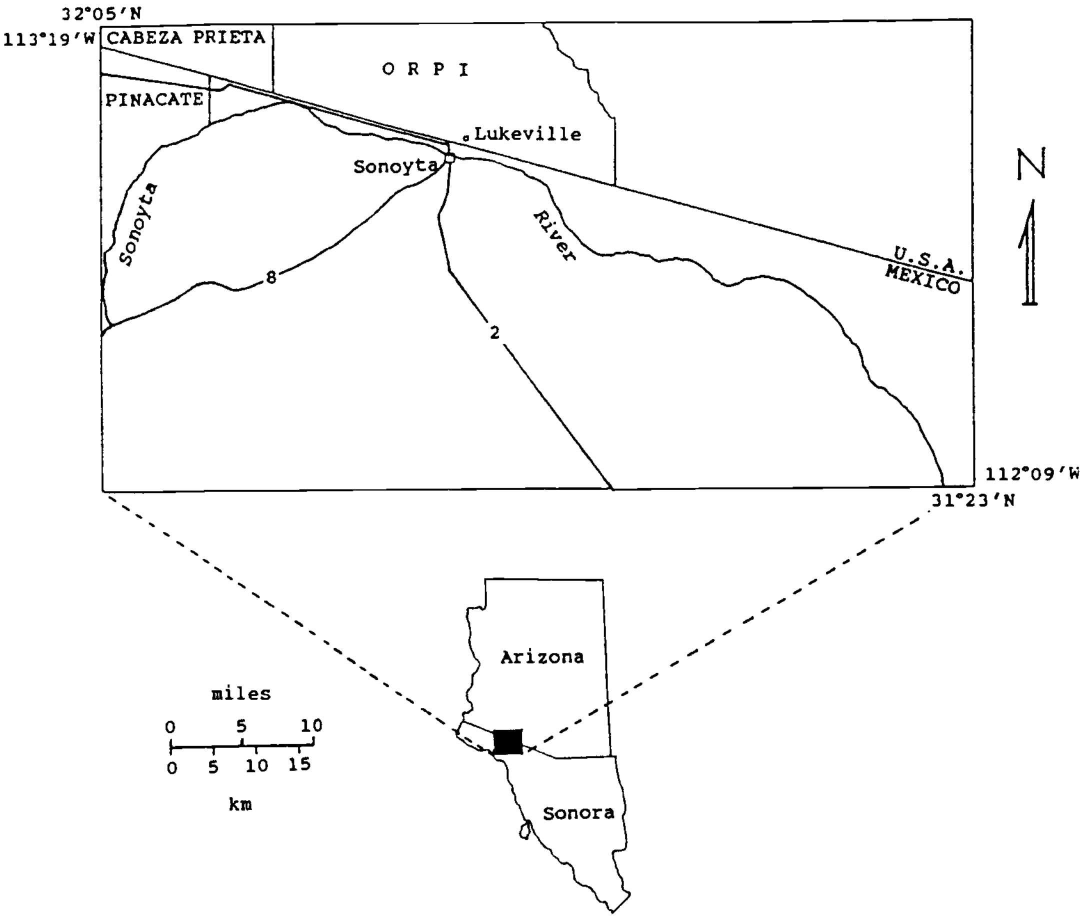

Figure 1. Extent of the study area.

of the two images allow overlay operations to compare geographic changes between the two dates of the images. With the intention of increasing contrast between different vegetation and other land cover classes on the 1972 and 1992 images, color composite images were created by combining bands 1 (0.5-0.6 um), 2 (0.6-0.7 um) and 4 (0.8-1.1 um) of the two images (Lillesand 1987).

To define changes between the two images, it was necessary to identify and classify the objects present on those images. By doing a preliminary unsupervised classification, six different land cover classes were adopted: croplands, bajadas with vegetation, plains with vegetation, riparian vegetation, hills, and bare soil. The choice of criteria used to distinguish these land cover classes was based principally on topography (slope), reflectance values, the association to other features on the image (like streams), and straight borders on irrigated fields. After two field trips to the site and revision of the ancillary data to obtain ground truth data, it was possible to identify training areas for a supervised classification.

The study used the classification method of seeding polygons because it involved small effort in the selection of the spectral values assigned to a land cover or land use class. For example, a polygon or border surrounding a known area of plains vegetation can be used to identify the variety of spectral values associated with this land cover class. These spectral values form the basis for selecting pixels with similar spectral values and assigning those pixels to the plains vegetation class. The training polygons should be as homogeneous as possible, containing only pixels that represent a particular land cover or land use class. The spectral signatures representing the desired classes were generated and the pixels of these signatures were sorted into classes using maximum likelihood classification decision rules (Erdas 1991). An error matrix of incorrect classification due to omission and commission was performed on the 1972 image. In accordance with Marsh et al. (1994), the error matrix analysis included errors of omission and commission, overall error measure, variance, and a Kappa index of agreement (KIA) (Eastman 1993).

Change analysis by image differencing (Jensen 1986; Campbell 1987; Singh 1989) was used to detect land cover and land use differences between 1972 and 1992. This method calculates the difference in reflectance values between two sets of Landsat data by subtracting the imagery of one date from that of another on a pixel by pixel basis. The subtraction process results in positive and negative values for pixels with reflectance value changes and zero values for pixels with no change. This procedure produces values for each band that are approximately Gaussian distributed, where pixels of no brightness value change are distributed around the mean and pixels of change are found in the tails of the distribution (Jensen 1986). In this study, change detection was performed by subtracting the 1972 classification image from the 1992 classification image.

Results and Discussion

Conspicuous differences in the extent of the land cover class areas can be seen between the two different years. Croplands appear as straight-bordered polygons. Bajadas with vegetation extend across slope gradients descending from hills to the river and other streams and to the valleys. Plains with vegetation are located in the valleys, between the bajadas and streams. The riparian vegetation class is typically found along the river and other streams located in the valleys, but it is also identified in the hill areas in the southern part of the image. Hills appear as an irregularly shaped, dispersed group of pixels that are defined by the pixels with the lowest reflectance values. The bare soil class is located mainly in the valleys and is defined by the pixels with the highest reflectance values.

For the years between 1972 and 1992, the classification method recorded 58.9 percent of the area as unaltered. Changes occurring in natural vegetation areas and not associated with obvious human activity affected 40.7 percent of the area, and less than 1.0 percent of the change was associated with human activities, primarily agriculture (Table 1). The positive change was in croplands, riparian vegetation and hills; but on the other hand, bajadas with vegetation, plains, and bare soil decreased in area (Figure 2). Among the six classes analyzed in this study, croplands was the least stable class: The classification process revealed that between 1972 and 1992 less than 4 percent remained unchanged. The most stable class was riparian vegetation.

Although the absolute percentage values for the fate of 1972 land cover and land use in 1992 were different in all cases, the relative ranking among the 1992 classes was identical for the fate

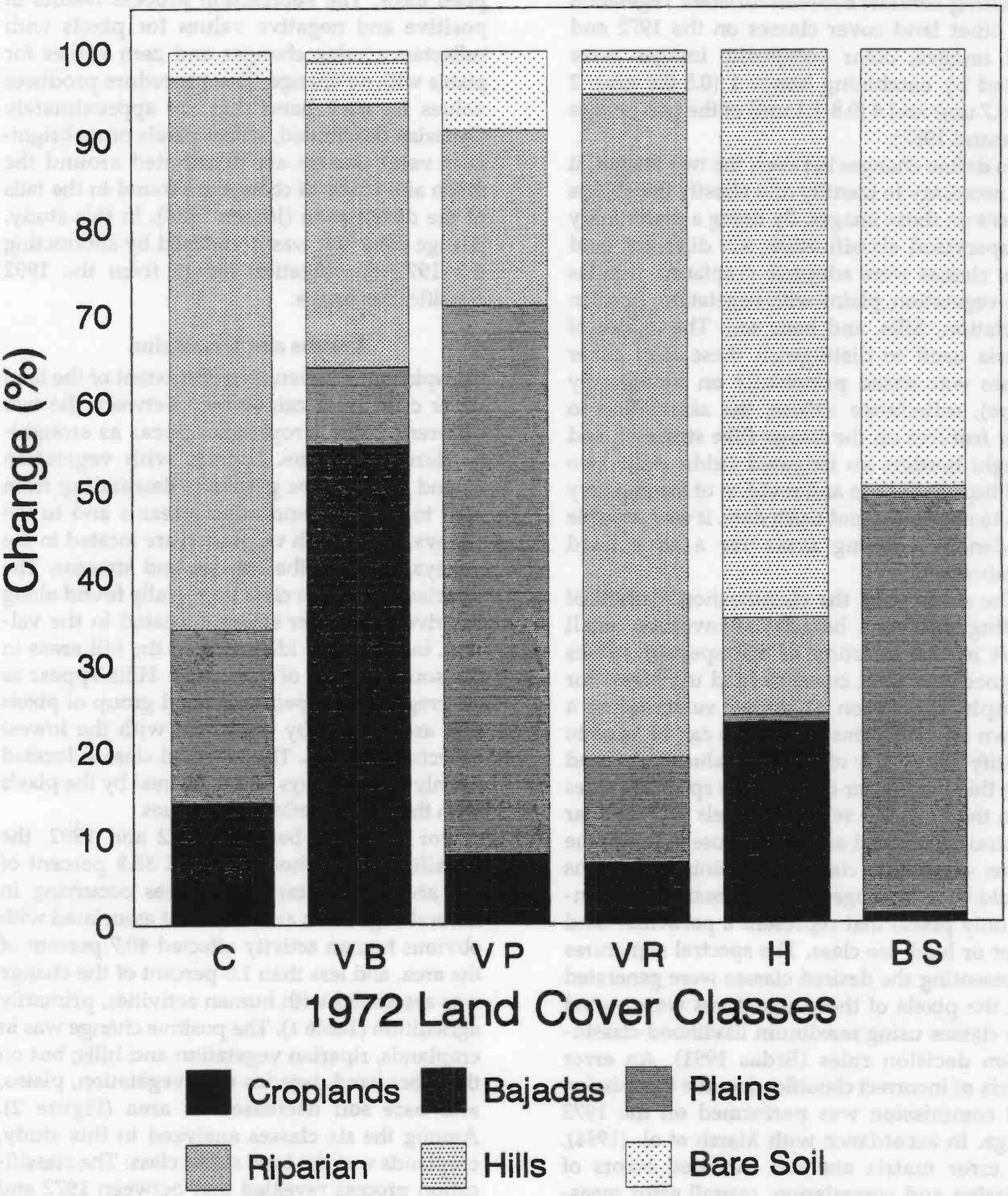

Figure 2. The fate of the 1972 land cover class in 1992 expressed as percent of 1972 total area after doing image classification by seeding polygons. C = croplands, VB = bajadas, VP = plains, VR = riparian, H = hills, BS = bare soil.

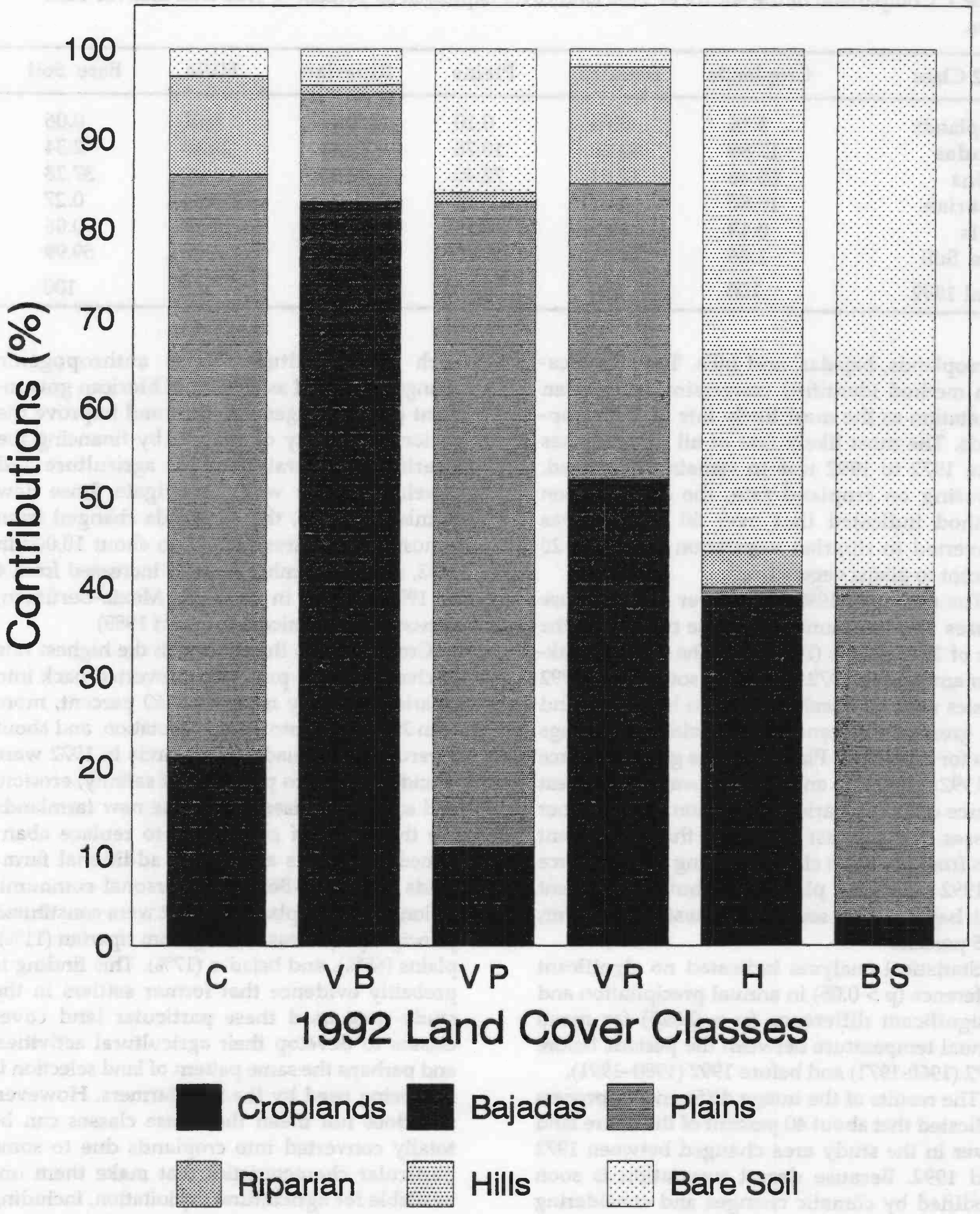

Figure 3. Source of the 1992 land cover classes expressed as percentage of 1992 total for each class using the seeding polygons classification method. C = croplands, VB = bajadas, VP = plains, VR = riparian, H = hills, BS = bare soil.

Table 1. Comparison of the source of 1992 land cover expressed as percent of 1992 total area for each class.

1972 Class	Croplands	Bajadas	Plains	Riparian	Hills	Bare Soil
Croplands	3.16	0.06	0.10	0.47	0.02	0.06
Bajadas	17.59	83.20	10.76	50.86	39.43	2.34
Plains	65.46	12.01	72.40	33.23	1.20	37.28
Riparian	10.80	0.97	1.44	13.29	3.54	0.27
Hills	0.13	3.45	0.10	1.86	55.78	0.06
Bare Soil	2.86	0.31	15.20	0.29	0.03	59.99
Total 1992	100	100	100	100	100	100

of croplands, bajadas, and hills. The classification method identified conversion to riparian vegetation as the most likely fate of 1972 croplands. The most likely fate of all other classes from 1972 to 1992 was to remain unchanged. Focusing on cropland fate, the classification method indicated that over 60 percent was converted to riparian vegetation and over 20 percent to plains vegetation.

The source of 1992 land cover and land use classes was less similar than the results for the fate of 1972 classes (Figure 3). The relative rankings among the 1972 classes as sources for 1992 classes were identical only for the hills class, and the greatest difference in the relative rankings was for croplands. Plains was the greatest source of 1992 croplands and bajadas was the greatest source of 1992 riparian vegetation. For all other classes, the greatest source of the 1992 extent was from the same class. Focusing on the source of 1992 croplands, plains contributed 65 percent and bajadas, the second greatest contributor, 17.5 percent.

Statistical analyses indicated no significant difference ($p > 0.05$) in annual precipitation and a significant difference ($p > 0.025$) for mean annual temperature between the periods before 1972 (1960-1971) and before 1992 (1980–1991).

The results of the image differencing process indicated that about 40 percent of the entire land cover in the study area changed between 1972 and 1992. Because desert vegetation is soon modified by climatic changes and considering that precipitation in the study area is the only factor of the environment that can cause a rapid change on vegetation (Cloudsley 1977), it is presumed that most of the changes were due to natural causes. Less than 1.0 percent of the area changed as a result of direct human activities such as agriculture. These anthropogenic changes occurred as a result of Mexican government policies to generate jobs and improve the regional economy of Sonoyta by financing the clearing of natural areas for agriculture and developing new wells to irrigate those new farmlands. Thus, the croplands changed from almost 300 hectares in 1972 to about 10,000 in 1992, and the number of wells increased from 4 in 1972 to 170 in 1992 (F. Mexía-Berúmen, personal communication; SARH 1989).

Cropland was the class with the highest rate of change, being principally reverted back into riparian areas by more than 60 percent, more than 20 percent into plains vegetation, and about 8 percent into bajadas. Croplands in 1972 were abandoned due to problems of salinity, erosion, and soil fungi diseases and the new farmlands are the result of conversion to replace abandoned farmlands and create additional farmlands (F. Mexía-Berúmen, personal communication). New croplands in 1992 were constituted principally by areas coming from riparian (11%), plains (65%), and bajadas (17%). This finding is probably evidence that former settlers in the study area used these particular land cover classes to develop their agricultural activities, and perhaps the same pattern of land selection is still being used by the new farmers. However, this does not mean that these classes can be totally converted into croplands due to some particular characteristics that make them unavailable for agricultural exploitation, including steepness, salinity, soil texture, and scarcity of water sources for crop irrigation. Although the anthropogenic changes obtained in this study do not represent a significant percent in terms of area, they are important in terms of environmental impact because they have generated a considerable number of ecological problems including the depletion of the groundwater table; disappearance of former perennial water bodies and streams that were sources of water and habitat for wildlife and plant species; reduction on the wildlife population species in the area, modification and suppression of natural habitats and ecosystems, ecosystem pollution by extensive and intensive use of agrochemicals, and weed dispersion and introduction into natural adjacent ecosystems.

There are several techniques to classify satellite imagery, all of them differing in processing time, algorithms used, and accuracy yielded. In this study, image classification was performed using the seeding polygons classification method. This widely used classification method proved to be uncomplicated, was easy to understand and manipulate, and can yield good results with an acceptable level of accuracy in a relatively short period of processing time, which is a good characteristic desired in every classification method. The principal disadvantage of this method is that when polygons are not homogeneously drawn (when enclosing pixels for a given class), the number of errors of omission and commission will increase and the level of accuracy of that classification will be too small to be considered acceptable for satisfactory results. When this occurs, new operations have to be performed until good results are obtained. Thus, this method depends principally on the user's ability and eyesight to distinguish between pixels with very similar reflectance values. The seeding polygons classification method yielded an overall accuracy of 81 percent in both 1972 and 1992 images.

Accuracy tends to degenerate when grid-cell resolution approaches the image pixel dimension (Owe 1984). In this study, pixel size (57m x 79m) was big enough to include several dissimilar classes, each with its own spectral properties. A pixel's spectral intensities could indicate one of the contained classes or an average of all, resulting in an unrelated surface. Most of the more common errors are related to these spectral anomalies. This result could explain the fact that large areas in the hills appear with the same reflectance values as riparian vegetation zones along the Sonoyta River. Thus, under more homogeneous land use conditions, more regional applications, or using higher resolution satellite imagery, the seeding polygons classification method could yield more accurate results.

In comparison to other life zones, the desert displays changes in land cover that are not consistent and may only manifest recent variations in rainfall, and that may not be significant for a longer period of time (Hastings 1980). In environments like the study area, climatic variations from year to year are substantial, and as a consequence, a natural change can be evident, as occurred in these two dates studied.

There was a consistent difference between precipitation means (19.2), but this difference was small considering the variability of the measurements (STDEV1 = 76.6, STDEV2 = 99.2). The computed t-value (-0.53) has a p-value of 0.60, indicating very little evidence of a difference in precipitation between 1972 and 1992. However, extreme changes in precipitation pattern in some years (i.e. 31.9 mm in 1968 and 487.0 mm in 1983) could have affected the vegetation land cover classes, resulting in spectral differences between 1972 and 1992 images that could be interpreted as a natural change. For example, the wet condition in 1983 may have increased vegetation cover, resulting in less bare soil in 1992 than 1972.

Short time periods (i.e. each 5 years) are recommended for change detection in order to create simulation models of the change processes, and therefore have a better understanding of how different factors are interacting to cause class modification and predict possible changes in the future.

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