Change Analysis in the United Arab Emirates: An Investigation of Techniques

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Abstract

Much of the landscape of the United Arab Emirates has been transformed over the past 15 years by massive afforestation, beautification, and agricultural programs. The "greening" of the United Arab Emirates has had environmental consequences, however, including degraded groundwater quality and possible damage to natural regional ecosystems.

Personnel from the Ground-Water Research project, a joint effort between the National Drilling Company of the Abu Dhabi Emirate and the U.S. Geological Survey, were interested in studying landscape change in the Abu Dhabi Emirate using Landsat thematic mapper (TM) data. The EROS Data Center in Sioux Falls, South Dakota was asked to investigate land-cover change techniques that (1) provided locational, quantitative, and qualitative information on land-cover change within the Abu Dhabi Emirate; and (2) could be easily implemented by project personnel who were relatively inexperienced in remote sensing. A number of products were created with 1987 and 1996 Landsat TM data using change-detection techniques, including univariate image differencing, an "enhanced" image differencing, vegetation index differencing, post-classification differencing, and change-vector analysis.

The different techniques provided products that varied in levels of adequacy according to the specific application and the ease of implementation and interpretation. Specific quantitative values of change were most accurately and easily provided by the enhanced image-differencing technique, while the change-vector analysis excelled at providing rich qualitative detail about the nature of a change.

Introduction

During the past 15 years, the landscape of the United Arab Emirates has undergone a remarkable transformation. More than 18 million date palms and 10 million acacia, eucalyptus, and other trees have been planted in patchwork forests as part of a massive afforestation and beautification program. The expansion of agriculture has been similarly impressive. To date, more than 100,000 hectares of desert have been transformed into cultivated land in the United Arab Emirates, and the process is continuing at a steady pace. Farmland and forests now cover approximately 4.5 percent of the country's total area, compared with a negligible vegetative coverage only 30 years ago. Despite the harsh climate and relatively small area, the United Arab Emirates now produces 20 percent of all dates in the world and has become an exporter of many vegetable and fruit crops.

The "greening" of the United Arab Emirates has not come without environmental cost, however. Observations suggest a direct correlation between the increased agricultural activities and large nitrate and conductivity increases in ground water (Bady *et al.*, 1997), and the vast increases in forest and agricultural land have important implications for regional ecosystems. Identification and analysis of landscape change have thus become key components in dealing with the environmental consequences of the changes. From the early 1980s to the present time, Landsat thematic mapper (TM) data have provided repetitive, regional-scale coverage of high-resolution multispectral images. These data provide an excellent baseline source from which to analyze land-cover changes over the past 15 years.

The Ground-Water Research Project (GWRP) is a joint effort between the National Drilling Company of the Abu Dhabi Emirate in the United Arab Emirates and the U.S. Geological Survey. The project's mission is to identify and monitor potential ground-water sources for agricultural and municipal use within the Abu Dhabi Emirate. Project staff had acquired 1987 and 1996 Landsat TM coverage of the Abu Dhabi Emirate for the purposes of identifying and analyzing land-cover changes over the past 10 years. Their primary interest was in helping to identify key locations in which to place groundwater monitoring wells by identifying areas of significant land-cover change. Secondary requirements included providing information on the growth of forest and agricultural inventories, identifying areas of urban growth, and creating public relations materials.

The GWRP asked the EROS Data Center to investigate various change-analysis techniques that not only provided suitable land-cover change information, but also could be easily implemented by GWRP personnel who had limited experience working with Landsat TM data. A variety of methods were used to generate different change-analysis data sets. Example data sets and the procedures used to develop them were then presented to GWRP personnel for consideration, along with specific recommendations. This paper examines the utility of the different change-analysis techniques in meeting the requirements of the GWRP.

Study Area

The Emirate of Abu Dhabi is the largest of the seven emirates making up the United Arab Emirates, covering an area of 87,340 square kilometres, or 86.7 percent of the country's total area. Numerous islands dot the Arabian Gulf in the northern part of the Emirate. Most of the surface in the United Arab Emirates is a sand desert. Although prevailing winds are relatively consistent, dune patterns and alignment vary considerably from region to region, with massive transverse dunes near Liwa in the south, longitudinal dunes in the southwest, and smaller eroded dune ridges in the northern emirates. Coastal and interdunal areas are often marked by

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sometimes dazzlingly white sabkhas, low-lying saline flats where the sand has been cemented by the precipitation of calcium carbonate and other salts from water tables close to the surface. The sand transitions to gravel plains and finally to the Hajar mountains in the extreme eastern portion of the country; these mountains possess the world's largest surface exposure of rocks from the oceanic crust (ophiolite). Vegetation is sparse in the interior of the country, with increasing amounts of grasses, halophytes, and small trees and shrubs toward the coast. Scattered waddies (especially in the Hajar Mountains) and oases hold pockets of intermittent (and occasionally permanent) surface water and associated vegetation.

Agriculture is concentrated in and around Al Ain, in a narrow strip along the east coast, in the oasis of Dhaid, and in the gravel plains in Ras al Khaimah. Much of the United Arab Emirate's soil can be cultivated, provided there is water, and additional pockets of agriculture occur wherever adequate ground water is found. The western portion of the Abu Dhabi Emirate contains wide stretches of planted forests. Other areas of the rectangular-shaped planted forests can be found in and around cities, along roads, and wherever adequate ground water is found.

Data Description and Preprocessing

Portions of eight Landsat TM scenes are needed to provide complete coverage for the Abu Dhabi Emirate in the United Arab Emirates. The GWRP had purchased TM scenes from 1987 and from 1996 for each of the path/rows covering the Emirate. For this investigation, path 160, row 043 was chosen because it covered the Al Ain area where the initial investigations were to be carried out and encompassed the variety of land-cover changes that were to be studied (Figure 1). The scene dates were 29 August 1987 and 04 March 1996; unfortunately, one is an early spring date while one is an early fall date. The importance of utilizing phenologically similar images is widely recognized (Pilon *et al*, 1988; Vogelmann, 1988; Milne and O'Neill, 1990); however, these were the only scenes available to the project at the time. The phenological differences of the natural vegetation between the two scene dates were mitigated by the warm and relatively constant desert climate. However, detection of agricultural changes between the two dates was somewhat muddied by the differing crop conditions between the March and August dates. Extremely harsh summer conditions prohibit many agricultural activities during that season. Because of that, many of the salad crops (tomatoes, cabbage, etc.) were harvested by the 04 March 1996 date. Similarly, many of the same crops were not yet planted by the 29 August 1987 date. For the change-detection techniques to identify agricultural areas, secondary evidence, such as disturbed or tilled soil, was often the only clue that agricultural activities were occurring.

Most of the processing was performed using ERDAS Imagine software. Imagine was the only software the GWRP had available, and any change-analysis techniques investigated had to be performed in Imagine. The one exception was a TM debanding algorithm that was performed using EROS' Land Analysis System (LAS) software. This algorithm implements a two-dimensional finite impulse response (FIR) filter that removes the banding pattern in TM data with a minimal effect on image content. The algorithm wasn't easily emulated in Imagine and was thus performed on each scene using LAS. To maintain consistency with later products, EROS staff provided debanded images to the GWRP for each of the other seven path/rows in the Abu Dhabi Emirate.

Accurate spatial registration of the two images is crucial to avoid artificially creating areas of change caused by misregistration (Gordon, 1980; Singh, 1989). Ground control point data for this study were collected manually at major road intersections in the Emirate with the use of the Global Positioning System (GPS). However, not enough points for a quality registration were available within the study scene area. It was decided to use the GPS control points to first register an eight-scene TM mosaic covering the entire Abu Dhabi Emirate that had been created for a previous study. The 1987 TM scene was then registered to the registered TM mosaic. Even a scene-to-scene registration proved difficult because of a lack of quality registration points in the desert areas. However, the major dune ridges are believed to date from the most recent glacial period more than 10,000 years ago and are no longer in motion or are being eroded; as such, they were used as ground control in lieu of more suitable points. The 1996 TM scene was then coregistered to the 1987 scene using manually collected control points.

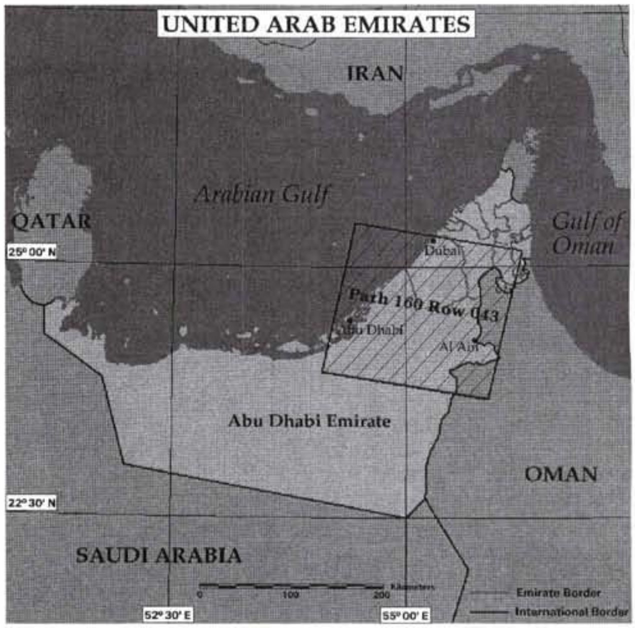


Figure 1. United Arab Emirates and footprint of Landsat TM path/row 160/043 that was used in this investigation.

True land-cover changes can be difficult to interpret if masked by differences in atmospheric conditions between the two dates. A relative calibration between image dates can be performed by applying a band-by-band linear transformation to one image date to "calibrate" it to the second date (Caselles and Garcia, 1989). This approach has the advantage of correcting atmospheric effects as well as other factors (detector mis-calibration, sun angle, Earth-Sun distance, etc.) that could be sources of error in change-analysis studies. The calibration is achieved by using digital number values of pseudo-invariant features, which are assumed to have constant ground reflectance through time. In this study, the 1987 TM scene was calibrated to the 1996 TM scene using bright desert sand areas and dark ophiolite rock areas as radiometric control sets to derive the gains and offsets for the linear transformation. This approach to scene normalization proved both effective and simple for an inexperienced user to implement.

Change-Analysis Techniques

A review of the literature shows numerous papers discussing the various change-analysis techniques commonly used (Howarth and Wickware, 1981; Singh, 1989; Mouat *et al.*, 1993). Most of these papers have focused on the utility of the different methods in satisfying specific categories of applications.

Few have focused on the ease of implementation and subsequent interpretation.

The GWRP required locational, quantitative, and qualitative information from the change-detection techniques implemented. Locational information required included regions of intensifying agricultural activities and afforestation, information that will be used in deciding where to place groundwater monitoring wells. Quantitative information required included the number of hectare increases in agricultural and forest cover. Qualitative information included general land-cover change supporting links between increased agricultural activities and decreased water quality, general patterns of urban growth, and the changes in or loss of natural habitats. With such a wide variety of goals, it was recognized that one change-detection technique alone would not likely satisfy all research interests. A number of change-detection techniques were examined and individually evaluated for each of the aforementioned objectives. Techniques were also evaluated for ease of implementation and interpretability. The change-detection techniques investigated here include univariate image differencing, "enhanced" image differencing, vegetation index differencing, postclassification analysis, and change-vector analysis.

Note that all images displaying results of the individual techniques are small subsets of the full scene used to depict the effectiveness of each method more clearly. The region shown is approximately halfway between Al Ain and Abu Dhabi, and exhibits the significant changes in agricultural and forest land that were of the most interest to the project. Plates 1a and 1b represent the 1987 and 1996 Landsat TM scenes for this small area.

Individual Techniques Tested

Univariate Image Differencing

Univariate image differencing involves subtracting a pixel's digital number (DN) value on one date from the corresponding pixel DN on the second date. The subtraction results in positive and negative values in areas of surface reflectance change and zero values in areas of no change. Using 8-bit Landsat TM data, the potential range of difference values is −255 to +255. A constant is normally added to keep output values in the positive range. The process is expressed mathematically as

$$\Delta x_{ijk} = x(1)_{ijk} - x(2)_{ijk} + C$$

where Δx is the change pixel value, $x(1)$ is the value at time 1, $x(2)$ is the value at time 2, C is a constant, $i = 1 \ldots nl$ number of lines, $j = 1 \ldots nc$ number of columns, and k is a single band, e.g., TM band 3.

The resulting difference image distribution has pixels of no change, minor surface change, and noise (i.e., atmospheric and other non-surface radiance characteristics that weren't successfully corrected in the image calibration procedure) distributed around the mean, while pixels of significant surface change are distributed in the histogram tails. As with many of the change-detection techniques investigated, a crucial component of this technique is the selection of a threshold value between change and no-change pixels. Numerous techniques have been used in selecting a change threshold. For this investigation, an interactive procedure, as advocated by Woodwell *et al.* (1983), was chosen. Various thresholds were set interactively and evaluated on the image display; the threshold best defining areas of change was selected.

Past studies have used a single band for the difference study (Jenson and Toll, 1982) or a color composite of three separate difference images from three spectral bands (Williams and Stauffer, 1978). It was thought that the difficulties an inexperienced user would have interpreting the colors of the color composite outweighed the additional information that the technique might provide; therefore, the single-band differencing technique was used. For this study, TM band 3 was chosen as the band to use for applying the approach. One of the primary goals of the GWRP study was to identify areas of new vegetation (i.e., agricultural crops and trees). Chlorophyll absorption of red radiant flux by green vegetation makes TM band 3 useful for discriminating between vegetated and non-vegetated surfaces. In addition, previous studies have shown the usefulness of a visible red band (Multispectral Scanner (MSS) band 5) in change-detection analysis in both vegetated environments (Toll *et al.*, 1980) and urban environments (Jenson and Toll, 1982). Pilon *et al.* (1988) concluded that a visible red band (once again, MSS band 5) provided the most accurate identification of spectral change for their semi-arid study area of northwestern Nigeria in sub-Sahelian Africa.

The 1996 TM image and the relatively calibrated 1987 TM image were differenced (1996 minus 1987). Output values from the differencing ranged from −122 to +118. Adding a constant of 128 resulted in an 8-bit output image with all positive values ranging from 6 to 246. A value of 128 theoretically represents an area of no change, values greater than 128 represent an increase in TM band 3 reflectance from 1987 to 1996, and values less than 128 represent a decrease in TM band 3 reflectance from 1987 to 1996. The threshold selection procedure outlined previously was used to select threshold values of two standard deviations above and below the "no-change" value of 128 (154 and 102 based on a standard deviation of 13).

Values above and below the threshold values were pseudocolored to create the final image (Plate 1c). Green represents areas where TM band 3 reflectance has decreased from 1987 to 1996. Increased chlorophyll absorption of red radiant flux explains most of the areas of decrease. Most of the green represents new agricultural land and forest land. Magenta represents areas where TM Band 3 reflectance has increased from 1987 to 1996. This occurred primarily where planted crops existed in the 1987 scene and were already harvested or were fallow in the 1996 image.

Evaluation

The univariate image-differencing technique provided an extremely straightforward method for providing locational information on areas of spectral change. The procedure is extremely easy to implement, and the results are fairly easy to interpret. The simplicity of the method, however, is also its main weakness; it fails to provide adequate qualitative information regarding the nature of the change. Many studies (Weismiller *et al.*, 1977; Riordan, 1980; Jensen and Toll, 1982) have suggested that simple image differencing alone doesn't adequately address all types of surface change occurring in a Landsat scene. This study supports those previous findings.

The difference image provides relative difference values between the 1987 and 1996 dates for one specific spectral band. However, a net decrease of 30 DN for TM band 3 from 1987 to 1996 can represent a number of different types of surface change. For the test area, changes of sand to agriculture, sand to forest, and sand to urban (asphalt) all exhibit similar difference characteristics and are indistinguishable on the final difference image. More rigorous techniques are required to adequately describe the nature of surface change.

The difficulty in adequately identifying the exact nature of a surface change also cripples the method's ability to provide useful quantitative information. The GWRP wanted quantitative information on the number of new agricultural areas and forests. The difference image produced by this method lends itself very well to providing hectares of change; however, the lack of information regarding the type of change

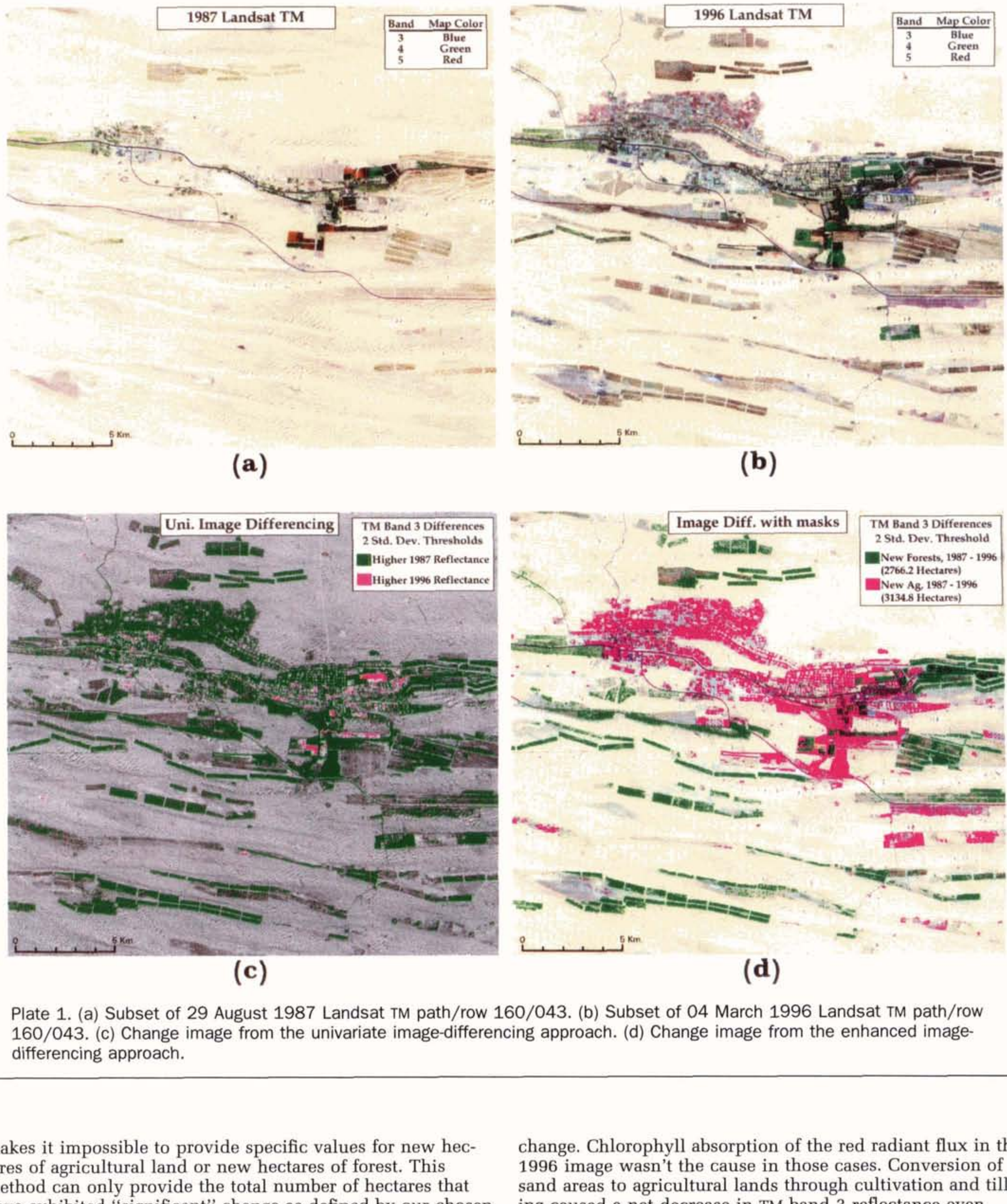


Plate 1. (a) Subset of 29 August 1987 Landsat TM path/row 160/043. (b) Subset of 04 March 1996 Landsat TM path/row 160/043. (c) Change image from the univariate image-differencing approach. (d) Change image from the enhanced image-differencing approach.

makes it impossible to provide specific values for new hectares of agricultural land or new hectares of forest. This method can only provide the total number of hectares that have exhibited "significant" change as defined by our chosen thresholds.

The procedure performed surprisingly well in identifying areas of new agriculture, considering that many of the crops were already harvested on the 1996 acquisition date. Many of the regions that weren't actively cultivated in the 1987 image and were cultivated but already harvested in the 1996 image were still identified as exhibiting significant change. Chlorophyll absorption of the red radiant flux in the 1996 image wasn't the cause in those cases. Conversion of sand areas to agricultural lands through cultivation and tilling caused a net decrease in TM band 3 reflectance even without a surface cover of crops. It should be noted, however, that some of the new agricultural areas were still missed as the 1996 harvested agricultural land was too similar to the 1987 bare (sand) surfaces. Anniversary date images with actively growing crops would most likely have provided much better results. New forest areas were also detected fairly well, although small portions of weak signature

TABLE 1. COMPARISON OF MEASURES OF NEW FOREST LAND AND NEW AGRICULTURAL LAND FOR THE DIGITIZED REFERENCE MASKS, THE ENHANCED IMAGE-DIFFERENCING TECHNIQUE, AND THE POST-CLASSIFICATION DIFFERENCING TECHNIQUE

	Reference Masks	Enhanced Image Diff.	Post Classif. Diff.
New Forest Land	3428.73 hectares	2766.20 hectares	3581.64 hectares
New Agricultural Land	3909.33 hectares	3134.80 hectares	6268.77 hectares

forest land that existed in 1987 were extracted as being changed due to forest growth and stronger signatures in the 1996 image.

The selection of change threshold values was problematic, although no more than with any other change-detection algorithm. The selected thresholds of two standard deviations above and below the mean adequately capture most of the surface change in the image without including many "non-change" areas. However, scattered portions of the most recently planted forests weren't captured as a significant change with the selected thresholds. Some of the "new" cropland in the 1996 image that had already been harvested was also not captured as a significant enough change. Raising the threshold to values greater than two standard deviations from the mean captured more of the problem forest and agriculture pixels but also began to capture increasing amounts of "non-change" areas. The two-standard-deviation threshold was an acceptable compromise between capturing too much as change and not capturing enough. It should also be noted that inexperienced personnel were also somewhat uncomfortable with the threshold selection procedure because of its subjective nature.

"Enhanced" Image Differencing

Although univariate image differencing alone failed to provide adequate information regarding agricultural and forest changes, it provided valuable locational information regarding surface change. Use of land-cover information for the 1996 image date in combination with the difference image created in the previous step offers the potential for identifying locational information on change and also some qualitative information regarding the nature of the change. For example, consider an area exhibiting a significant decrease in TM band 3 reflectance in the difference image (as defined by the selected threshold) and classified as forest in a 1996 land-cover classification. The majority of forests existing in the 1987 imagery don't show up as a change in the TM band 3 difference image, as the growth wasn't spectrally "significant" as defined by our thresholds. 1996 forest areas exhibiting a significant decrease in TM band 3 reflectance can thus be safely classed as a new forest planted in the timeframe between 1987 and 1996. Agricultural areas can be handled similarly. In the 1996 agricultural areas (as defined by a 1996 land-cover classification), a significant decrease in TM band 3 reflectance from 1987 to 1996 is likely because of chlorophyll absorption from new, actively growing crops or from decreased reflectance due to a shift from undisturbed and relatively bright sand to cultivated and tilled agricultural lands. Such areas are thus likely new agricultural areas that didn't exist in the 1987 imagery.

A downside to this approach is the need for a complete 1996 land-cover classification, as the creation of such a classification would most likely prove to be very time consuming. The need for a complete classification can be avoided by limiting the types of change we attempt to explain. The GWRP was primarily interested in analyzing the newly planted forests and the new agricultural areas. A few simple digital masks corresponding to specific land-cover types can be used to mask out areas of unwanted change and distinguish between agricultural and forest lands. On-screen digitizing proved to be a simple and extremely effective method for creating digital masks that were used to refine the difference image and provide information on the type of surface change. For example, the acacia forests are extremely easy to identify on the Landsat images. They exhibit sharp and well-defined boundaries, contrast very well with the surrounding sand, and exhibit characteristic rectangular shapes. They also tend to be clumped in large groupings, which consist of anumber of forest blocks surrounded by sand. Digitizing large, generalized polygons around the forest regions enables an analyst to separate new forest regions from other types of change on the univariate difference image. Similar polygons were drawn around the few urban centers and a few areas of natural change (mostly coastal areas), because the change occurring in these areas was also confused with new forest and new agricultural land in the band-3 differencing. A simple spatial model consisting of decision rules using the significant decrease threshold from the difference image and the digital masks was then created, resulting in an image that depicted areas of new agriculture and forest. Areas of change were pseudo-colored and overlaid on the 1996 Landsat TM imagery (Plate 1d). The number of hectares of new agriculture and forest was computed by checking the image histogram and calculating the hectares in each change type, using the following relationship between pixel area and hectare area:

(30-metre pixel = 900 square metres = 0.09 hectares)

One can thus simply multiply the number of pixels in each "class" by 0.09 to get the number of hectares.

Evaluation

One of the GWRP's primary goals of providing locational and quantitative information regarding new forest and agriculture was satisfied fairly well using this method. As discussed previously, the univariate image differencing procedure performed quite well at identifying areas of new forest and agriculture, but it couldn't distinguish between them (nor between other types of change). The creation of the digital masks to help distinguish types of changes was quite simple and effective. The use of such digitized masks may not be feasible in areas exhibiting more heterogeneity with regard to land cover, but the spatial distribution and relatively low number of land-cover types in the United Arab Emirates made it a relatively quick, simple, and effective process for this application.

A simple check was done of the method's effectiveness at quantifying the number of hectares of new agriculture and of new forest land. "Reference" digital masks corresponding to forest land and agricultural land for each image date were created by careful manual interpretation and by digitizing each land-cover type from the 1987 and 1996 TM images. These masks differ from the masks used in the creation of the product in that each individual forest or agricultural block was carefully digitized in the reference masks, but just a few large, generalized polygons around large regions of relatively homogeneous land-cover types were used to create the product. The resulting reference masks were differenced, and the hectares of "new" agriculture and "new" forest land were extracted. Reference values were then compared to values from this procedure (Table 1). Values represented are only for the small image subset represented in the example output images. It should be noted that this simple check in no way tests the locational accuracy of where the changes occurred.

Although the procedure provided acceptable estimates of new agriculture and forest areas for the GWRP, a few factors caused some underestimation in each value. Because areas of change were calculated from the previous univariate image differencing image, the product created with the enhanced image differencing suffered from the same problems. Phenological differences in the agricultural crops (many 1996 crops had already been harvested) caused an underestimation in the amount of new agricultural land detected. As happened with the univariate image differencing, some of the newest forest plantings weren't captured as change due to a relatively small decrease in TM band 3 reflectance, so the value for hectares of new forest is also a slight underestimation.

One strength of this enhanced image differencing was the GWRP personnel and their knowledge of the area. They had extensive field experience in the Abu Dhabi Emirate and could create very accurate digital masks for use with this method.

Downsides to the technique included the time required to create the digital masks, although in this area it was a relatively small investment for the return of information. It is a relatively simple procedure to identify the two types of land-cover change, but a complete and more thorough description on the nature of change would be better provided by another technique such, as post-classification differencing.

Vegetation Index Differencing

Vegetation indices have long been used in monitoring vegetation conditions. The indices are based on chlorophyll absorption of the red part of the visible spectrum and strong reflectance in the near-infrared part of the spectrum. Variability in a vegetation index between image dates can be used in the monitoring of vegetation change. The normalized difference vegetation index (NDVI) (Tucker, 1979) has been used in numerous previous studies involved with analyzing vegetation condition and change (Briggs and Nellis, 1991; Chilar *et al.*, 1991; Lee and Marsh, 1995). The general NDVI formula for Landsat TM data is as follows:

$$(TM4 - TM3) / (TM4 + TM3).$$

Values from the basic NDVI calculation range from −1 to +1. To place output values in an 8-bit unsigned integer format, a constant of 1 was added to the base output value, giving potential values of 0 to + 2. A multiplier of 127 was then applied to stretch the data through the 8-bit range. The NDVI and scaling calculation used was thus:

$$[(TM4 - TM3) / (TM4 + TM3) + 1] * 127.$$

The preceding formula was applied to the 1987 and 1996 TM images to create NDVI images for the two dates. The univariate image-differencing procedure outlined previously was then applied to the two NDVI images (1996 NDVI − 1987 NDVI). Change thresholds of one standard deviation above and below the mean were selected through the interactive selection and evaluation procedure used previously. Values above and below the threshold values were pseudo-colored to create the final image (Plate 2a). Green represents areas where NDVI values increased from 1987 to 1996. As expected, this corresponds to regions of new agriculture or new forests. Magenta represents areas where NDVI values have decreased from 1987 to 1996. This occurred primarily where planted crops existed in the 1987 scene and were already harvested or were fallow in the 1996 image.

Evaluation

The NDVI differencing proved useful for identifying new areas of actively growing agricultural crops. The phenological differences between scene dates with regard to agricultural crops was problematic, however, because the procedure didn't adequately detect new agricultural areas that didn't have actively growing crops in the 1996 image. There was also difficulty in detecting the newly planted acacia forests. Individual trees in the acacia forests are planted relatively far apart, allowing much of the underlying sand surface to be exposed to the sensor. The acacias are also quite scrubby, with relatively small amounts of green leaf area. In addition, many of the forests shown in the test region were very recent plantings; as such, the trees were relatively immature. All three of these factors contributed to unexpectedly low NDVI values in the 1996 image, and new acacia forests were subsequently not discriminated very well using the NDVI differencing technique. Similarly, the lack of change in NDVI values associated with urban growth prohibited adequate detection of new urban areas.

NDVI differencing performed slightly better than univariate image differencing with regard to qualitative descriptions of surface change, primarily due to the types of change that NDVI differencing wasn't able to detect. New forest areas, new agricultural areas, and new urban areas all exhibited similar difference signatures in the univariate image differencing. The NDVI differencing wasn't able to detect new urban areas and performed relatively poorly in detecting new forest areas. When we selected a fairly stringent change threshold (two or three standard deviations above the mean) that eliminated the poorly delineated forest areas, the NDVI differencing method performed well at producing an image depicting new agricultural lands, although once again phenological differences between the two image dates prohibited detection of all but the green and currently growing fields.

Implementation of the NDVI differencing method was only slightly more difficult than the univariate image differencing. Less experienced persons seemed to have few problems interpreting the NDVI difference image once the link between the NDVI and green biomass was understood.

Post-Classification Analysis

Post-classification change analysis involves the comparison of independently produced land-cover classifications for two different dates. Numerous studies have used post-classification differencing in the analysis of change. Weismiller *et al.* (1977) reported good results in identifying areas of change in coastal areas. Pilon *et al.* (1988) used post-classification differencing in combination with a simple enhancement technique to isolate areas of human-induced change from areas of natural change. Massart *et al.* (1995) used the results of post-classification differencing in combination with various thematic data layers to analyze the impacts of agricultural development on tropical forest environments.

The method performs well in areas where differencing and ratioing techniques often fail. Although differencing or ratioing techniques alone may be able to illustrate areas of surface change, they don't adequately describe the nature of that change. Post-classification change analysis is capable of depicting a complete descriptive matrix of changes between two dates. The method also has the advantage of compensating for varied atmospheric conditions between dates or even the use of different sensors between dates because each classification is independently produced and mapped to a common thematic reference. The analyst also has more control on what type of change will be represented in the final change image by controlling the thematic classes that are represented in each classification. For example, unwanted changes between agricultural crop types may show up with the differencing or ratioing methods but can be nullified with post-classification analysis by creating classification images with only one agricultural class.

Post-classification differencing isn't nearly the panacea that the above statements imply, however. The method has been widely criticized because it tends to compound any classification errors that may have occurred in the two initial classifications (Gordon, 1980; Pilon *et al.*, 1988; Singh, 1989).

Processing time must also be considered when debating the use of post-classification differencing, because independent classifications of two complete Landsat scenes can be extremely time consuming and labor intensive.

For this study, we did unsupervised classifications of the 1987 and the 1996 Landsat TM. The ISODATA algorithm was used to cluster each scene into 50 spectrally similar clusters. Clusters were individually evaluated and tentatively labeled with one of the following simple land-cover types: agriculture, forest, urban, water, and other (primarily bare sand or rock surfaces). Multiple clusters were confused between more than one land-cover type; once again, digitized masks representing general areas of the various land-cover types were used to resolve the confusion. For example, ophiolite areas were often confused with the more newly planted Acacia forests in the sand desert. The ophiolite area was confined to the eastern portion of the scene and was easily digitized with one large general polygon, which could be used as an ancillary piece of information to split a confused cluster. Similarly, a few large, generalized polygons were drawn around the regions of forest and urban centers to assist with other confused clusters. Such a manual digitizing process would prove impossible in more complex landscapes, but was quick, simple, and efficient for the relatively simple landscape of the United Arab Emirates. It was also thought that such a simple, unsupervised classification strategy would be easier for the inexperienced analyst to implement.

The resulting 1987 and 1996 classifications were used as input to a "matrix" algorithm, which creates an output file containing classes corresponding to each unique combination of input classes from the two dates. The resulting image was pseudo-colored to provide unique colors for each of the possible land-cover changes between 1987 and 1996. A 5 by 5 change matrix key was then created, which graphically depicted the type of change each color represented (Plate 2b). For example, red represents areas that have changed from "other" (primarily sand) in the 1987 image to "agriculture" in the 1996 image. Note that water pixels weren't present in either date for the subset area represented in the figure, so the change matrix key was simplified to show the four classes present (urban, forest, agriculture, and other).

Evaluation

The post-classification difference image provided much of the information requested by the GWRP. The extensive personal experience of GWRP personnel in the area also would have been a great asset in creating classification images for subsequent scenes. Unfortunately, this was outweighed by two factors: (1) the great amount of time and expertise needed to create the product, and (2) the inherent errors in the final product. The first of these factors played the greatest role in the decision not to recommend this procedure to the GWRP. The time required for an experienced user to create the final product was easily five times that needed for any of the other methods tested. Also, after discussion with GWRP personnel, it was felt that a lack of experience in classification work and a limited amount of training time would adversely affect the quality of a post-classification change product, despite GWRP personnel's extensive knowledge of the Abu Dhabi Emirate.

There were also problems with the accuracy of the final product. Quantitative values of change from the previously created reference digital masks were compared with values from the post-classification differencing image (Table 1). Because of classification errors in the two individual classifications, the post-classification difference image over-represented some types of change. For example, many shaded sand areas were misclassified as agriculture in the 1996 image due to similar spectral signatures between shaded sand areas and agricultural areas without existing crop cover. Those areas thus incorrectly show up as new agriculture ("other" to "agriculture") in the post-classification difference image (selected red areas on Plate 2b). Similarly, some of the newly planted forests in the 1987 image were incorrectly classified as "other" due to their weak signature. With the stronger signature and resultant "forest" classification in the 1996 image, these areas show up as new forest ("other" to "forest") in the difference image (selected orange areas on Plate 2b). The problems possibly could have been lessened by more "cluster-busting" (an unsupervised classification of pixel members of one cluster) of the confused clusters or by extensive digitizing and recoding of classification errors in the individual classifications, but these procedures would have required an even larger investment of time.

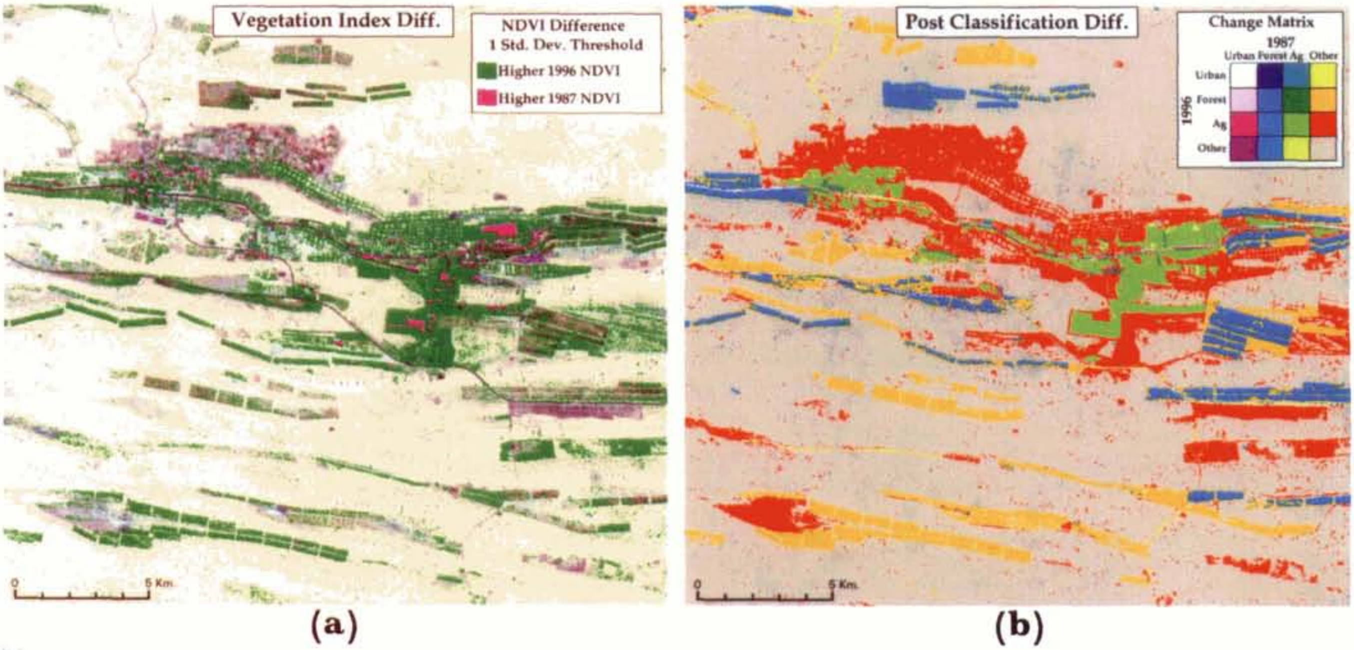
Change-Vector Analysis

Surface change can be described by a spectral change vector, which represents the direction and magnitude of change from the first to the second date. If the magnitude of a calculated spectral change vector exceeds a critical threshold value, a surface change is presumed to have occurred. The threshold value can be empirically selected or rigorously modeled. The direction of the change vector identifies the type of change that has occurred. Change-vector analysis has been previously used in forest change detection in northern Idaho (Malila, 1980) and in South Carolina (Colwell and Weber, 1981).

The procedure used here was an adaptation of previous change-vector analyses studies in the brightness and greenness plane (Dwyer *et al.*, 1997). The 1987 and 1996 TM scenes were transformed into brightness, greenness, and wetness components using the principal components-based Tasseled Cap transformation (Kauth and Thomas, 1976; Crist and Cicone, 1984). Brightness and greenness differencing was performed between the two dates, and change vectors were computed. Change vectors were then decomposed into magnitude and direction components. Pixels corresponding to actual landscape change were identified by modulating the magnitude component with an empirically derived threshold value of two standard deviations above the mean. The threshold selection procedure was the same interactive procedure used with previous change-detection techniques. Note that the empirically derived threshold value replaces the calculation of an image noise model as described by Dwyer *et al.* (1997) in order to simplify the procedure for the GWRP. The change vectors were then encoded using hue, saturation, and value. The direction of change was encoded as hue, the magnitude of change as saturation, and the original 1996 TM scene was rescaled to value (intensity) to provide contextual information. A hue, saturation, value (HSV) to red, green, blue (RGB) transformation was then performed for displaying the change image. The resulting colors correspond to the direction of change, while the richness of the colors corresponds to the significance of the change (Plate 2c). For example, very recent forest plantings exhibit a very pale bluish tone (nearly gray) corresponding to a decrease in brightness and an increase in greenness, while more established plantings exhibit a stronger bluish tone. Gray tones correspond to areas that had not experienced any significant change as defined by the selected threshold of the change-vector magnitude component.

Evaluation

The change-vector analysis provided a graphically rich product that was relatively high in qualitative information. Areas of change were readily identifiable, and use of the reference color wheel allowed for a description of the nature of that change with regard to the brightness and greenness planes. The technique thus performed relatively well at providing lo-



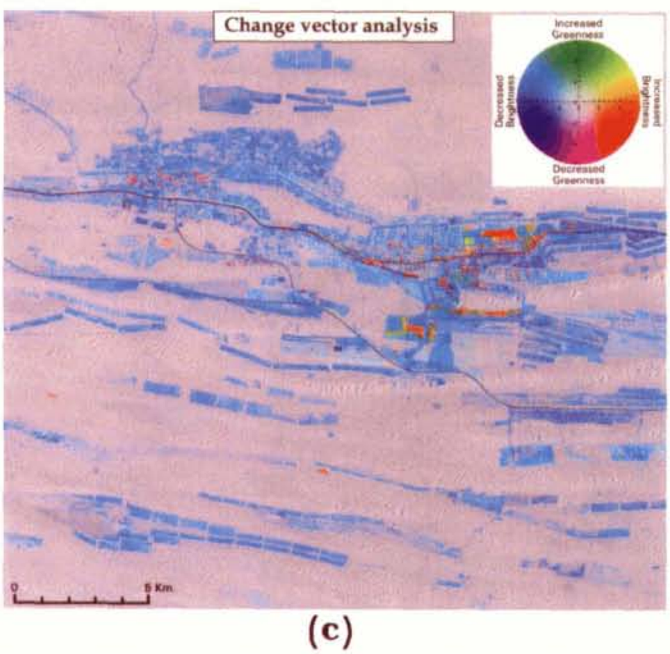


Plate 2. (a) Change image from the vegetation index differencing approach. (b) Change image from the post-classification differencing approach. (c) Change image from the change-vector analysis approach.

cational and qualitative information. Similar types of change with regard to the brightness and greenness planes, however, are easily confused. The subtle differences in the blue and cyan colors representing new agricultural areas and those representing new forest areas are extremely difficult to visually interpret, because both involve similar changes with regard to brightness and greenness. It should be noted, however, that this problem might have been less severe had anniversary dates of 1987 and 1996 images been available. Many of the crops in the 1996 image were already harvested during the acquisition time. The crops that were still actively growing during the 1996 acquisition are represented by a fairly distinct, bright cyan color in the change image.

This method doesn't allow easy derivation of discrete quantitative values. For example, visual identification of new agricultural areas is relatively straightforward, but deriving total acreages of new agricultural lands is not. The product of this procedure was a three-band image resulting from a HSV to RGB transformation where hue represented the direction of the change and saturation represented the magnitude of the change. Deriving quantitative values for the amount of change would require the use of the original saturation image and a selected threshold value. Similar thresholds would be required within the original hue image to distinguish between various types of change.

The procedure was fairly easy to implement, although it required a number of steps to create the final product. The procedure proved somewhat more difficult for the inexperienced user to understand, because the reasoning behind each of the processing steps wasn't as obvious as in some of the other methods. Interpretation also proved to be a problem for those unfamiliar with the Kauth-Thomas brightness-greenness planes. Interpretability was aided significantly by the addition of a legend with color patches keyed to specific types of change; i.e., cyan corresponds to a transition from bare sand to vegetated, darker blue corresponds to a transition from bare sand to urban surfaces (asphalt), etc.

Discussion

The goal was to provide a simple, easily implemented, easily interpreted approach to detecting various types of land-cover change in the United Arab Emirates. The different techniques each provided different types of information and varied in accuracy and ease of implementation. The various products for the different methods were created, descriptions of the processing flow were compiled, and results were presented to GWRP personnel. GWRP's primary goals were to identify key locations in which to place ground water monitoring wells by identifying areas of significant land-cover change, to provide information on the growth of forest and agricultural inventories, to identify areas of urban growth, and to provide public relations materials. Based on accuracy requirements, informational content, and ease of implementation and interpretation, specific recommendations were made.

Providing qualitative and locational information proved to be far easier than providing quantitative values of change for specific types of land-cover change. A recommendation was made to use the change-vector approach to provide the majority of the locational and qualitative information that was required. Change-vector analysis provided a product that accurately depicted locations of change, was fairly simple to implement, and was extremely rich in qualitative information. Areas of significant land-cover change were very clearly depicted, information that was key to helping the GWRP identify possible locations for groundwater monitoring wells. The rich qualitative content allowed for discrimination between the different forms of land-cover change. The method was excellent at depicting areas of urban growth. The graphically rich product was also considered to be the best for creating public relations materials. The primary downside to this approach was its interpretability for GWRP personnel. Relating a specific color on the change image to the reference color wheel and inferring a specific land-cover change (i.e., sand to agriculture) was a more complex task than interpreting some of the other products. The task was made more difficult by the sometimes very subtle differences in shading between different types of land-cover change. Interpretation became much less difficult with greater experience, however. The procedure also was unable to provide a measure of the number of hectares of new agricultural or forest land.

Providing a method that accurately provided the number of hectares of new forest and agricultural land was more difficult. The enhanced image-differencing technique proved best at providing this information. The qualitative information the method provided couldn't match that provided by change-vector analysis, but it yielded fairly accurate quantitative values for forest and agricultural change. The use of the simple digital masks takes advantage of GWRP personnel's extensive knowledge of the region. The method was very simple to implement and very easy to interpret.

It was recognized that several factors hindered the success of these investigations, with the primary problem being that of scene dates. The recommendation was made to purchase new Landsat TM data sets, specifically anniversary-date Landsat TM data acquired during the winter when crops are actively green and growing. As mentioned throughout this article, it was very difficult to accurately detect areas of new agriculture due to the March and August dates of the two Landsat scenes. Neither had a large percentage of cropland with current crop cover; much had already been harvested by the March 1996 date, and not much had been planted yet by the August 1987 date. It was extremely difficult to detect new agricultural areas because the bare fields without crops were spectrally similar to other land-cover types in the area (shaded sand, some ophiolite areas, etc.). It became the same problem that land-cover classification studies face, the problem of "land use" versus "land cover." Much of the land *use* was for agriculture, but, because of the land *cover* at the times of acquisition, it was extremely difficult to detect "new agriculture" based on spectral information alone.

The nature of the acacia forests also proved to be a problem. The acacias were scrubby trees with relatively small amounts of green leaf area, were spaced rather widely, and were spectrally similar to various other land-cover types; furthermore, forest growth in the change-analysis timeframe sometimes caused confusion between the detection of new forests versus forest growth. Fortunately, the shape, size, and locations of the acacia forests were spatially unique and, when coupled with the relatively simple landscape of the United Arab Emirates, allowed for the success of the digital masking techniques.

It is important to recognize specific customer requirements or usage when providing products derived from remotely sensed data. As this investigation showed, the product with the most information isn't necessarily the best product if production time, cost, and interpretability are considered. A proper balance of each of these factors is necessary to ensure the best outcome to an investigation.

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