Deriving Current Land-Use Information for Metropolitan Transportation Planning through Integration of Remotely Sensed Data and GIS

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Abstract

Transportation planners and metropolitan planning organizations require up-to-date land-use information to allocate transportation resources and to forecast the location and type of growth within metropolitan areas and associated increases in transportation volumes. For rapidly changing areas, extant geographic databases may not contain current land-use information. Other layers in the GIS database have potential for aiding image-based procedures for updating land-use layers. Results from the first of two case studies suggest that land-use change detection using high spatial resolution imagery is useful for detecting individual change features, but that automatic delineation of these features yields imprecise boundaries, such that interactive delineation is likely to be required. Results from the second case study indicate that many GIS data layers maintained by metropolitan planning organizations provide useful information for determining current land use when combined with interactive identification of land-use category from high resolution image data.

Introduction

In their 1997 Annual Report, the Bureau of Transportation Statistics identify land-use data as being critical to understanding the relationship between public policy and the ability of transportation to serve businesses and the public (U.S. Dept. of Transportation, 1997). According to Newkirk and Wang (1990), land-use data are critical to transportation planners because their ability to monitor the impact of planning controls and to influence the directions of change is compromised without current information on the location of land uses and trends in land-use change.

Land use in metropolitan areas continually changes over time and space, and transportation planners and metropolitan planning organizations (MPOs) must be able to update their databases to reflect current land use. In recent years, a number of local and state agencies and major MPOs have incorporated data from remote sensing instruments to generate and update land-use layers (American Planning Association, 1998). However, most types of remote sensing imagery enable only five to 15 categories of land use to be discriminated with acceptable accuracy (Welch, 1982). MPOs often require information on as many as a 40 to 80 or more detailed classes of land use (American Planning Association, 1998; SANDAG, 1998).

Geographic information system (GIS) databases maintained by MPOs contain a large variety of data layers that can be used as indicators of land use. These information sources include current and projected zoning, historic land use, property value, employment, and existing infrastructure such as transportation networks. Multiple data layers typically stored in GIS databases that are maintained by MPOs may be used as ancillary data sources to augment and enhance land-use classification and updating by interactive visual or computer-assisted routines that are based primarily on interpretative elements of imagery. However, if remote sensing and GIS data sources are to be utilized to achieve accurate identification of the highly detailed land-use categories required by transportation planners, new techniques of data integration and manipulation must be developed.

The objective of this paper is to examine the state of practice and future promise of deriving the detailed land-use GIS layers required by metropolitan planning organizations through the integration of remotely sensed data and other GIS data layers. Based on this goal, this paper reviews the basic information requirements of transportation planners, provides case study examples of data analysis techniques which may be utilized by transportation planners or the value-added service support industry, and relates current and future techniques of data integration and manipulation to satisfy such information needs. The case studies were elements of two projects conducted as part of the NASA Affiliated Research Center at San Diego State University, in conjunction with two commercial partners, Shenandoah Mountain Geographics, Inc. of Arlington, Virginia and Aerial Fotobank, Inc. of San Diego, California.

Land-Use Data and Transportation Planning

Metropolitan planning organizations (MPOs) and State Departments of Transportation (DOTs) utilize computerized transportation models to predict the influence of development patterns, transportation systems, and demographics upon regional travel demand. These models ingest information from as many as 100 detailed land-use classes, in conjunction with transportation network and demographic data, to forecast and predict the interactions between transportation, economic development, and environmental concerns (Parrott *et al.*, 1996). These models are complex, data-intensive formulations of assumptions that are founded on the spatial organization of residences, places of employment, and locations of commercial activity

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(Spear and Lakshmanan, 1998; Harper and Manheim, 1990; Heikkila *et al.*, 1990). Results from these land-use driven models enable transportation planners to forecast the level of usage at activity centers as a function of location, distance to urban population centers, and socio-economic composition of the surrounding community (Stopher *et al.*, 1996). Ultimately, these transportation planning models are used to evaluate the effect of public investment in highway and transit systems, public water and sewer service, and zoning changes in future land use, including residential, industrial, and commercial district locations.

Remote Sensing and GIS for Deriving Current Land-Use Data

Several transportation planning organizations throughout the U.S. have used satellite imagery to support land-use identification. Foresman and Millette (1997) describe the use of Landsat TM in conjunction with geographic information systems to derive land-use and other spatial data for regional planning of 25 towns in Vermont. Image processing techniques and visual interpretation were used to identify these classes in the imagery. Gallimore *et al.* (1993) utilized Landsat TM imagery to identify and categorize land-use information in several alternative corridors for regional transportation improvements in North Carolina.

Remotely sensed imagery is a valuable data source for summarizing regional land use. However, moderate to low resolution imagery (10 to 1,000 meters) has been shown to be too coarse to identify many of the detailed land-use classes required within transportation models (Jensen and Cowen, 1999). Jensen and Cowen (1999) suggest that resolutions of 5 to 20 meters are adequate for Level II classification and that resolutions of 1 to 5 meters enable sufficient identification of many Level III classes. Forster (1985) indicated that imagery must have a spatial resolution of 3 m or less if it is to be used to accurately identify Level III or even some Level II land-use classes from the USGS Land-Use/Land-Cover Classification System (Anderson, 1976). Therefore, moderate resolution satellite imagery is not appropriate for meeting the categorical identification requirements of MPOs, which tend to be near Level III, Level IV, or higher.

Updating Changes in Land Use

Moderate resolution imagery is most useful to transportation planners and MPOs for the purpose of locating areas of land-use change between the current time and the time of the last detailed land-use survey. Many techniques have been established for detecting land-use/land-cover change, including image overlay (Howarth and Wickware, 1981), image differencing (Jensen and Toll, 1982), image ratioing (Howarth and Boasson, 1983), change vector analysis (Malila, 1980), direct multidate classification (Estes *et al.*, 1982), and post-classified comparison (Howarth and Wickware, 1981). Following change detection, imagery having spatial resolutions on the order of 0.25 to 5 meters may be used in conjunction with other data sources to aid identification of the new land-use type (Jensen and Cowen, 1999).

GIS coverage maintained by urban planning organizations and local governments can be used in conjunction with high spatial resolution imagery (0.25 to 5 m) and queried to provide indication of site specific land use. These databases contain information on such variables as locations of employment, existing land use, census population estimates, water lines, road and railway classes, tax assessor property value, lot size, developable land, constraints to development, zoning, and point features such as government buildings, hospitals, and amusement parks. All of these data layers provide some indication of site-specific land use and may be incorporated with remotely sensed imagery to provide land-use information to transportation planners.

Functionally, the San Diego Association of Governments (SANDAG) is representative of most nationwide MPOs; however, they have pioneered efforts to integrate remotely sensed data with GIS to update, rather than regenerate, land-use data layers (Parrott *et al.*, 1996). To update GIS data layers with high categorical detail, SANDAG utilizes regional parcel and lot-level vector layers having high positional precision. Land-use types are identified and encoded by analysts that visually interpret georeferenced satellite data "on-screen" and are aided by information from ancillary data sources. These data sources include county assessor's master property records, Thomas Brothers map files (commercially supplied digital maps), employment and activity center inventories, aerial photography, USGS digital orthophotographic quarter quadrangle images, and SPOT High Resolution Visible digital image data in panchromatic and multispectral modes (SANDAG, 1998).

Case Studies

Two case studies are provided to illustrate the potential of remote sensing and GIS for providing land-use information relevant to transportation planners, such as the one implemented by SANDAG. The case studies mostly address technical issues and pertain to the two primary phases of an interactive land-use updating approach. While the general approach is not specific to a particular application, the procedures were tested and assessed in the context of transportation planning. For such an application, updated land-use data must have high attribute (category) specificity and accuracy, with the requirements for positional accuracy and precision of boundary delineation being less stringent. The first case study is an assessment of the utility of high spatial resolution imagery to *detect* and *delineate* parcels of land-use change. The second case study explores the information content of existing GIS data layers to aid in image-based *identification* of new land-use categories for areas determined to have changed.

The general study area is located in the northern portion of the City of San Diego and is bounded by the USGS Del Mar quadrangle. This area contains the districts known as Del Mar East, Sorrento Mesa, and Sorrento Valley. It contains a wide range of land uses and is characterized by recent rapid growth in residential and light industrial uses. Historic land use has been well documented with archived imagery from both aerial photography and satellite imagery sources and is archived in an extensive, multitemporal GIS database maintained by the San Diego Association of Governments (SANDAG).

Case Study 1: Change Detection with High-Resolution Imagery

The results presented here stemmed from the first phase of a more extensive study which evaluated procedures for exploiting high spatial resolution imagery to detect, delineate, and enumerate changes in specific features such as roads and commercial, residential, and office buildings. Imagery having spatial resolutions of 1, 5, and 10 meters were evaluated within this context using image processing and/or visual image interpretation techniques.

Scanned multispectral aerial photographs from 1997 and 1998 having a spatial resolution of 1 meter and a 1998 panchromatic Indian Remote Satellite (IRS-C) image having a spatial resolution of 5 meters were used for the change-detection work. One meter panchromatic images were created by scanning the 1997 and 1998 color photographs and taking the intensity band from an intensity, hue, saturation transformation. These 1-meter panchromatic images were aggregated to simulate a 5-meter image for 1997 and 10-meter images for both 1997 and 1998, while the IRS-C panchromatic satellite image provided the 5-meter data for 1998.

Digital images derived from scanned aerial photographs captured in 1998 were radiometrically normalized to 1997 scanned photographs using an image-to-image regression approach. With this approach, image brightness values from one date were matched to image brightness values from another date using the coefficients of an ordinary least-squares regression line. Change detection was performed by differencing the multitemporal image data. Change detection results from a portion of Del Mar study are illustrated in Figure 1.

Multitemporal difference images (Figures 1a, 1b, and 1c) reveal that many change features are highlighted similarly by images having 1, 5, and 10 meter spatial resolutions. For these examples, difference values greater than ± 1 standard deviation from the mean of the difference image were highlighted as change features. However, analysis of individual change features such as structures and roads revealed that the boundaries of most change features were not precisely delineated at any of the three spatial resolutions. Extensive image processing procedures were applied to these difference images to evaluate the feasibility of automated change feature extraction. These procedures generally employed classification and difference products, majority filters, grouping of like pixels (that meet a minimum area requirement) from the majority filtered products, and vectorization of the resulting thematic groups. Application of these semi-automated image processing procedures were only partially successful in more precisely delineating new land use features such as commercial structures (Figures 1a, 1b, and 1c), roads, houses, and large sudivisions and industrial complexes (not illustrated). The problems were largely associated with incomplete classification of the entire extent of features.

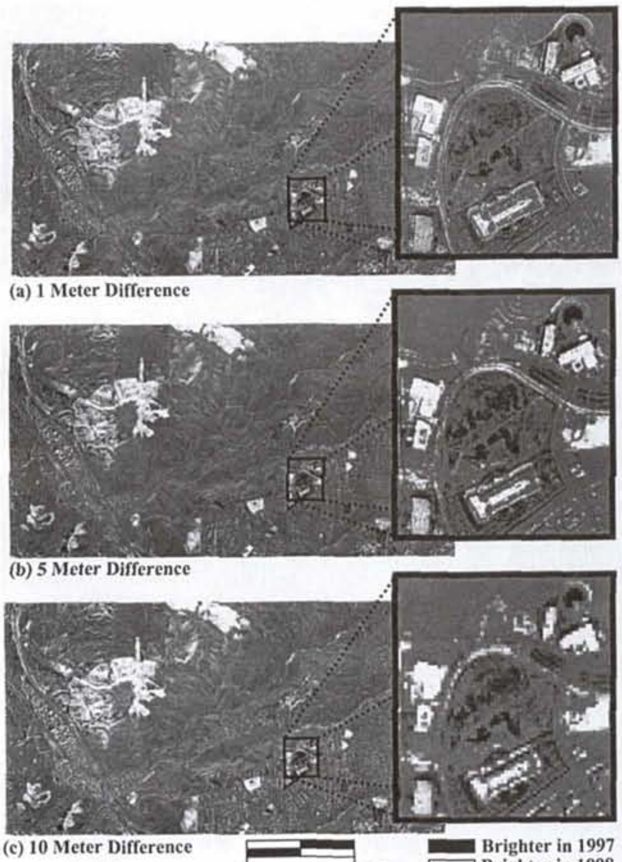

Figure 1. 1998 minus 1997 difference images at (a) 1-meter, (b) 5-meter, and (c) 10-meter resolutions. Non-change (±1 standard deviation from difference mean) is illustrated as gray in zoom chips.

The following conclusions were derived from this case study. High spatial resolution imagery, which is likely to be in use or available to transportation planners, may be used to highlight and detect large areas of change and individual change features such as roads and structures, provided that the geometric registration is highly precise. Accurate delineation of these change features using automated image processing techniques can be difficult, time consuming, costly, and, in many cases, not accurate. Therefore, change products generated using high spatial resolution imagery are best suited as a guide to interactive, manual delineation by an interpreter.

Case Study 2: Utility of Existing GIS for Updating Current Land Use

The focus of the second case study was on the utility and predictive power of existing GIS data layers in aiding human-assisted or automated image identification of current land-use types for polygons detected and delineated as having changed. Geo-spatial data layers for 1990 and 1995 were acquired from the SANDAG and the San Diego Geographic Information System (SANGIS), the geo-spatial data processing service for the City and County of San Diego, GIS databases.

SANDAG GIS layers for 1990 and 1995 land use were utilized as the primary reference data for the locations and types of land-use change between 1990 and 1995. To ensure that changes indicated by differences in land-use categories between these two data layers represented actual change, 1990 and 1995 land-use categories and polygon boundaries were validated with field observations and in the computer laboratory through interpretation of 1990 aerial photographs, 1995 digital orthophoto quarter quadrangle (DOQQ) images, and a SPOT XS 1995-minus-1990 difference image.

Spatial correspondence analysis was used to assess the relationship between the attributes of several geo-spatial data layers and the 1995 land use from the reference data. The 19 land-use categories utilized in this study and the summary codes assigned to them are provided in Table 1. The two layers with the greatest predictive power were found to be land-use forecast information derived by SANDAG in 1990 with the Planned Land Use Model (PLUM90) and point data on employment locations for 1995 (EMP95) with associated standard industrial code (SIC) attributes. The spatial correspondence analyses yielded co-occurrence matrices depicting the 1995 land-use categories, (the dependent or predicted variable), relative to the two independent or predictor variables (PLUM90 and EMP95). High correspondence suggested that the predictor class provided an indication of the new land use.

Results from the analysis of spatial correspondence of changed land use (LU95) and the planned land use (PLUM90) are presented by polygon count in Table 2 and by percent of predictor class in Table 3. The percent of class table provides the most useful measure of predictive power; however, the count of polygons is also important to include as it indicates the number of samples taken into account. The PLUM90 data layer provided strong predictive power for some, but not all, 1995 land-use categories. The single family residential (**11**), light industry (**21**), commercial (**50**), and public services (**61**) land-use classes showed high correspondence, indicating that the PLUM90 data layer would be a useful source of information for identifying these land uses within change areas determined from multi temporal imagery. The single occurrence of the Office class (**60**) was in agreement with the PLUM90 layer. While the correspondence between many of the other categories appears low, it is noted that many change polygons are classified as under construction or vacant/undeveloped in 1995. The predicted land use for many of these polygons may not have been realized because land use was transitional at the time of the 1995 image acquisition and updating.

TABLE 1. LAND-USE TYPE AND NUMERICAL CODE

Land Use	Code	Land Use	Code	Land Use	Code	Land Use	Code
Spaced Residen.	10	Heavy Industry	20	Office	60	Parks	76
Single Family Residen.	11	Light Industry	21	Public Service	61	Agriculture	80
Multi-Family Residen.	12	Extractive	22	Hospital	65	Vacant/Undev.	91
Mobile Home	13	Junkyard/Landfill	23	Military Use	67	Water	92
Group Quarters	14	Other	41	Schools	68	Under Construct.	95
Hotel/Motel	15	Commercial	50	Commercial Recreation	72		

TABLE 2. CORRESPONDENCE BETWEEN 1995 PLANNED LAND USE AND 1995 LAND USE BY POLYGON COUNT

PLUM 90	by Polygon - Count																						
LU 95	10	11	12	13	14	15	20	21	22	23	41	50	60	61	65	67	68	72	76	80	91	92	95
10		1																	1				
11		13	4																1				
12			8																3				
13																							
14																							
15						1		1															
20																							
21								15											2				
22																							
23																							
41			2			2		1						1					3			1	
50						2						3											
60												1	1						1				
61		2	1											3									
65								1															
67																							
68																	1						
72	1	1	1																1			2	
76			4																7			1	
80	2	1																	6				
91	1	3	8			2		2				1		1			1		8			2	
92																							
95	1	6	1			1		8				2		1					17			1	

TABLE 3. CORRESPONDENCE BETWEEN 1995 PLANNED LAND USE AND 1995 LAND USE BY PERCENT OF TOTAL PER 1995 PLANNED LAND-USE CLASS

PLUM 90	by Polygon - % of PLUM 90 Class																						
LU 95	10	11	12	13	14	15	20	21	22	23	41	50	60	61	65	67	68	72	76	80	91	92	95
10		4																	2				
11		48	11																2				
12			21																6				
13																							
14																							
15						13		4															
20																							
21								54											4				
22																							
23																							
41			5			25		4						17					6			14	
50						25						43											
60												14	100						2				
61		7	3											50									
65								4															
67																							
68																	50						
72	20	4	3																2			29	
76			11																14			14	
80	40	4																	12				
91	20	11	21			25		7				14		17			50		16			29	
92																							
95	20	22	26			13		29				29		17					34			14	

Employment data for 1995 were found to be useful for predicting particular land-use classes. Results from the spatial correspondence analyses are given in Tables 4 and 5. Industrial (**21**) type employment points corresponded to industrial land use for 80 percent of the 132 occurrences, while occurrences of hospital (**65**) type employment and land use corresponded for approximately 52 percent of the 284 points. The five occurrences of school (**68**) type employment all corresponded to "school" land use.

The correspondence between SIC codes from a point data layer and certain new land-use categories demonstrates the potential utility of SIC classification of employment for predicting industrial, park, and hospital land-use categories. Also, the simple presence of employment points within a polygon may be utilized to differentiate employment-based land uses from other land-use types such as residential, vacant/undeveloped, and transportation. Table 6 presents the count of employment per land-use class, the average number, and the standard deviation of points per polygon per land-use class. The large differences in the number of employment points per polygon between the hospitals, commercial, office, and light industry classes and all other classes are apparent in this table. These differences may be exploited to discriminate and aid in the identification of new land use.

A third data layer, the 1990 Land Use (LU90) polygon layer, was used to determine if the 1990 land-use category of poly-

Table 4. Correspondence between the 1995 Employment (Point) Data and 1990 Land Use by Category Point Count

Employment 95											Points - Count												
LU 95	10	11	12	13	14	15	20	21	22	23	41	50	60	61	65	67	68	72	76	80	91	92	95
10								1							1			1					
11								2			1	51		1	7			2					4
12												41		1	2			1					1
13																							
14														1	1								
15						4						5			1								
20																							
21						1		185	1		39	799	2	8	35			9		2			46
22																							
23																							
41											2	2											2
50											4	181		1	16			2					2
60						5		42			28	723	3	29	67			8					21
61												6	5	1									
65												12	1	3	148								1
67																							
68												4	11		4		5						
72						1						2	2					3					
76														1									
80												21						6		2			
91								1			1	9						1					2
92																							
95								1			2	18			2			1					

Table 5. Correspondence between the 1995 Employment (Point) Data and 1990 Land Use by Percent of Total per 1995 Employment Class

Employment 95									Points - % of Employment 95 Class														
LU 95	10	11	12	13	14	15	20	21	22	23	41	50	60	61	65	67	68	72	76	80	91	92	95
10																		3					
11								1			1	3		2	2			6					5
12												2		2	1			3					1
13																							
14														2									
15						36																	
20																							
21						9		80	100		51	43	8	17	12			26		50			58
22																							
23																							
41											3												3
50											5	10		2	6			6					3
60						45		18			36	39	13	63	24			24					27
61													21	2									
65												1	4	7	52								1
67																							
68													46		1		100						
72						9							8					9					
76														2									
80												1						18		50			
91											1							3					3
92																							
95											3	1			1			3					

gons adjacent to change polygons provides an indication of the 1995 land use. (Note that this data layer represents the dated land-use layer which is to be updated.) Summary measures of simple occurrence/non-occurrence of similar land use between change polygons and adjacent polygons were generated though manipulation of the polygon attribute tables.

Adjacency analysis was performed for a portion of the larger study area that was predominantly composed of residential land-use types. The binary occurrence or non-occurrence of 1990 land use adjacent to change polygons of the same land-use class in 1995 was derived from the GIS data layers. Results presented in Table 7 give fraction and percent occurrence of change polygons having the same 1995 land-use category as at least one adjacent polygon from the 1990 land-use layer. These results indicate that many of the change polygons were bordered by at least one polygon with the same land use in 1990. All change polygons which transitioned to agriculture in 1995 were bounded by agriculture in 1990. Fourteen of the 22 change polygons which transitioned to light industry were bordered by light industry in 1990. More than 50 percent of the change polygons labeled as under construction in 1995 were bordered by under construction in 1990. For many land-use classes, nearly 50 percent of the change polygons were adjacent to like land use in 1990.

These results suggest that land-use categorization decisions made with discrete rules that integrate image and ancillary data are inappropriate. Probabilistic rules integrated with image classification or into interactive visual image interpretation should be more effective.

Approaches to Incorporating GIS Layers in Image-Based Updating

The previous case study demonstrated that incorporating and integrating remotely sensed data with information derived from existing GIS databases provides enhanced capability for discriminating land-use types and greater frequency of database updates required to parameterize transportation models. In the context of identifying and encoding the new category associated with a changed land-use polygon, image analysts may select from a variety of possible approaches for incorporating ancillary data. Most available ancillary data for identifying land-use types are categorical (i.e., nominal scale), which limits the types of approaches that may be used in integrating such data with image data that are inherently continuous (i.e., interval or ratio scale) (Strahler *et al.*, 1980). While several approaches are available, only a few are likely to be suitable for deriving land-use information at the level of categorical detail

Table 6. Count, Mean, and Standard Deviation of 1995 Employment Data Points per Polygon

1995 Employment Data - Points per Polygon			
CLASS 95	COUNT	AVG.	ST. DEV.
Parks	1	1.00	—
Group Quarters	2	2.00	0.00
Space Rural Residential	3	1.00	0.00
Other Transportation	6	3.00	2.83
Commercial Recreation	8	1.33	0.82
Hotel/Motel/Resorts	10	2.50	1.73
Public Services	12	1.20	0.63
Vacant/Undeveloped	14	2.33	2.16
Schools	24	1.50	0.82
Under Construction	24	6.00	3.83
Agriculture	29	2.64	1.50
Multi-Family Residen.	46	1.84	1.43
Single Family Residen.	68	1.39	0.76
Hospitals	165	33.00	57.64
Commercial	206	18.73	23.65
Office	926	29.87	35.14
Light Industry	1127	17.34	29.26

Table 7. Fraction and Percent of Total for Which Adjacent Land Use Matched the Change Polygon's New Land Use

Adjacency: Occurrence vs non-occurrence		
Land Use Category	Number Adjacent/Total	Percent Occurrence
10	—	—
11	3/8	38%
12	3/7	43%
13	—	—
14	—	—
15	0/1	0%
20	—	—
21	14/22	64%
22	—	—
23	—	—
41	4/9	44%
50	2/3	67%
60	1/4	25%
61	1/1	100%
65	2/2	100%
67	—	—
68	0/1	0%
72	—	—
76	2/3	67%
80	5/5	100%
91	4/10	40%
92	—	—
95	12/20	60%

required for transportation planning applications. These approaches are described below.

GIS Querying
The simplest approach to implement and, possibly, the most effective is an integration of on-screen visual image interpretation and polygon digitizing combined with GIS querying. Any automation in the process is most likely to occur in the change-detection and delineation process which is based on multitemporal image data. Even if very-high resolution (e.g., 1 m) multispectral data are available for image interpretation,
(1) automated routines are generally not available and are not able to exploit high level image interpretative elements in the manner that a human interpreter can and (2) detailed land-use categories frequently cannot be identified successfully, even with visual interpretation, unless other source materials are available. Those extant GIS layers found to be indicative of new land-use categories with a high degree of confidence can be integrated into the interpretation process by enabling the analyst to query their attributes by pointing to locations which correspond to, or are adjacent to, the change polygon.

The effectiveness of the interactive querying approach depends on the amount of pre-processing that is required to prepare pertinent GIS layers for effective integration and on how conveniently and quickly a GIS attribute can be queried, displayed, and analyzed (Westmoreland and Stow, 1992). Because several GIS layers are likely to be required to identify a variety of land-use categories, some degree of pre-processing and some type of formal querying strategy that incorporates a customized on-screen display of GIS attributes will likely yield the most effective interpretations. This is in contrast to an *ad hoc* querying approach, where an analyst queries a specific GIS layer depending on particular image cues and the degree of uncertainty of their initial image interpretation.

Knowledge-Based GIS Models
A more automated and standardized approach than interactive querying is to develop knowledge-based models for integrating GIS layers and, possibly, the output of computer-assisted image classification. Boolean algebraic and other discrete rule-based models are the most common knowledge-based approaches (Jensen *et al.*, 1994). The rules, thresholds, and weights of such approaches can be derived from theoretical principles and relationships, or they can be based on empirically derived estimates. Westmoreland and Stow (1992) found that the prediction of a new land-use category from a knowledge-based model alone was not sufficiently reliable, but the model prediction was useful as an additional information attribute that was queried along with pertinent GIS layers. A standard criticism of knowledge-based approaches is their lack of generality. If the rules and model parameters were sufficiently generalizable for a given metropolitan area, such an approach may be worth evaluating.

Bayesian Classifier
A more mathematically formal approach than the knowledge-based approach is the Bayesian classifier which is based on parametric statistics and involves the estimate of probabilities of class (category) membership. The *a posterior* probability, which forms the basis of the Maximum-Likelihood classifier, is determined by spectral-radiometric features of training sets. The *a priori* probability may vary according to the spatially corresponding attribute of a categorical variable represented in a GIS data set (Middlekoop and Janssen, 1991). The probabilities may be estimated from a contingency table derived from the sampled, spatial co-occurrence of the new land-use category versus some explanatory categorical variable (e.g., adjacent or projected land use), as described previously in the second case study. The land-use class decision is based on the composite probability, which is the product of the image-based *a posterior* probability and the GIS-based *a priori* probability (Strahler *et al.*, 1980). A drawback of this approach is the difficulty in achieving a sufficient sample set for estimating *a priori* probabilities from contingency tables.

Logit Classifier
Similar to the Bayesian approach is the Logit classifier, in that continuous-value image data may be directly combined with categorical GIS data to identify a most likely land-use category. Based on a log-linear representation of the logistic regression approach, an advantage of the Logit classifier is that training data from the input image are not required to be normally distributed (i.e., a non-parametric approach) (Wrigley, 1985). The input data requirement for categorical GIS layers is also less

restrictive. As for the Bayesian classifier, commercial image processing packages have not implemented the Logit classifier.

Post-Classification Sorting and Neural Networks

Post-classification sorting is one technique to reclassify confused pixels based on domain-specific rules derived from ancillary data (often stored and implemented in a GIS) (Jensen, 1996). In recent years researchers have called into question the rule of allocating each pixel to a single category, reporting uncertainty in the course of presenting thematic maps, and the use of artificial neural networks as fuzzy classifiers and mixture models (Foody, 1996; Moody *et al.*, 1996; Foody *et al.*, 1997; Zhu, 1997; Foody, 1999). Fuzzy classification is a technique whereby partial and multiple class memberships are derived to suggest the strength of class membership for each pixel. This information can be useful when incorporating ancillary data in a post-classification sorting scheme. Foody (1995), for example, integrated a neural network fuzzy classification with ancillary data in a multi-layer perceptron (MLP) type of neural network to classify SAR imagery.

Expert System Approach

The most promising approach to the complex and high-level cognitive problem of identifying a very specific land-use category is the expert system. As a structured and formalized systematic approach to capturing the essence of a subjective process, an expert system can help to reduce subjectivity and increase efficiency. Many of the attractive elements of all of the approaches described previously can be incorporated into an expert system. For instance, interactive queries and knowledge-based models may be integrated into the expert system in a manner that should optimize classification decisions and efficiency. Similarly, the results of semi-automated classifiers that integrate image and GIS data such as Bayesian, Logit, and Neural Network classifiers can be incorporated (Wang, 1993; Gong *et al.*, 1996). As with all of these approaches, the key is determining which image and GIS inputs provide the most explanatory power for a given land-use category and in a given landscape and urban growth setting.

Summary and Conclusions

Transportation planners and government agencies require up-to-date land-use information in order to forecast the location and type of growth within metropolitan areas and the increases in the number of trips that would be generated from this population growth. For areas where land-use changes are common, existing geographic databases may not provide current information. Remotely sensed imagery and existing geographic databases can be utilized to provide a wealth of information regarding current land use and can be used to update land-use layers. Approaches to data integration reviewed in this paper provide the methods by which these data sources may be incorporated to determine land use.

Two case studies were presented to demonstrate the utility of remotely sensed and GIS data sources for detecting change areas and determining new land-use classes in the context of updating land use for input into transportation models. The first case study addressed the use of multitemporal, high spatial resolution imagery for detecting land units of change. Interactive and automated approaches to change feature delineation were evaluated. Results suggest that automated approaches do not provide sufficiently accurate boundary delineation and that manual interpretation and delineation of land-use change polygons is likely to be required. Results from the second case study indicate that information derived from extant GIS databases can add substantial information to the land-use identification process. Successful implementation of this approach requires an initial evaluation (such as described in the case study) of the predictive ability of site-specific GIS layers, and an understanding that indications from multiple sources may be required to accurately identify detailed land-use classes. In this study, data on adjacent and planned land uses and current employment data were all found to be valuable indicators of current land use.

While new sources of high-resolution image data are becoming readily available and will improve the accuracy and specificity of land-use updates, ancillary data sources will still be required to augment the image interpretation process. Several techniques for integrating remotely sensed and GIS data that will allow extraction and incorporation of information from both of these data sources were presented. Of these techniques, the most promising are likely to be the interactive GIS querying and expert systems approaches.

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References

American Planning Association, 1998. *Land-Based Classification Standards: Draft Classification*, American Planning Association Research Department, **http://www.planning.org/lbcs**.

Anderson, J.R., E.E. Hardy, J.T. Roach, and R.E. Witmer, 1976. *A Land Use and Land Cover Classification System for Use with Remote Sensor Data*, Geological Survey Professional Paper 964, U.S. Geological Survey, Washington, D.C., 28 p.

Estes, J.E., D. Stow, and J.R. Jensen, 1982. Monitoring land use and land cover changes, *Remote Sensing for Resource Management*, (C. J. Johannsen, and J. L. Sanders, editors), Soil Conservation Society of America, [city?], Iowa, pp. 100–110.

Foody, G.M., 1995. Land cover classification by an artificial neural network with ancillary information, *International Journal of Geographical Information Systems*, 9(5):527–542.

———, 1996. Approaches for the production and evaluation of fuzzy land cover classification from remotely-sensed data, *International Journal of Remote Sensing*, 17(7):1317–1340.

———, 1999. The continuum of classification fuzziness in thematic mapping, *Photogrammetric Engineering & Remote Sensing*, 65(4):443–451.

Foody, G.M., R.M. Lucas, P.J. Curran, and M. Honzak, 1997. Non-linear mixture modelling without end-members using an artificial neural network, *International Journal of Remote Sensing*, 18(4):937–953

Foresman, T.W., and T.L. Millette, 1997. Integration of remote sensing and GIS techniques for planning, *Integration of Geographic Information Systems and Remote Sensing*, (Jeffrey L. Star, John E. Estes, and Kenneth C. McGuire, editors), Cambridge University Press, Cambridge, pp. 134–157.

Forester, B.C., 1985. An examination of some problems and solutions in monitoring urban areas from satellite platforms, *International Journal of Remote Sensing*, 6(1):139–151.

Gallimore, W.P., D.T. Hartgen, and Y. Li, 1993. Applications of geographic information system-transportation analysis packages in superregional transportation modeling, *Transportation Research Record*, 1364:122–130.

Gong, P., R. Pu, and J. Chen, 1996. Mapping ecological land systems and classification uncertainties from digital elevation and forest-cover data using neural networks, *Photogrammetric Engineering & Remote Sensing*, 62(11):1249–1260.

Harper, E.A., and M.L. Manheim, 1990. Geographic information systems in transportation planning: A case for a geographic-based information services strategy for regional planning, *Regional Development Dialogue*, 11(3):188–217.

Heikkila, E.J., J.E. Moore, and T.J. Kim, 1990. Future directions for EGIS: Applications to land use and transportation planning, *Expert Systems: Applications to Urban Planning*, (T.J. Kim, L.L. Wiggins, and J.R. Wright, editors), Springer-Verlag, New York, pp. 225–240.

Howarth, J.P., and E. Boasson, 1983. Landsat digital enhancement for change detection in urban environments, *Remote Sensing of Environment*, 13(2):149–160.

Howarth, J.P., and G.M. Wickware, 1981. Procedure for change detection using Landsat digital data, *International Journal of Remote Sensing*, 2:277–291.

Jensen, J.R., and D.L. Toll, 1982. Detecting residential land-use development at the urban fringe, *Photogrammetric Engineering & Remote Sensing*, 48(4):629–643.

Jensen, J.R., D.C. Cowen, J. Halls, S. Narumalani, N. Schmidt, B.A. Davis, and B. Burgess, 1994. Improved urban infrastructure mapping and forecasting for BellSouth using remote sensing and GIS technology, *Photogrammetric Engineering & Remote Sensing*, 60:339–346.

Jensen, J.R., 1996. *Introductory Digital Image Processing: A remote sensing perspective*, Prentice Hall, Upper Saddle River, N.J., 316 p.

Jensen, J.R., and D.C. Cowen, 1999. Remote sensing of urban/suburban infrastructure and socio-economic attributes, *Photogrammetric Engineering & Remote Sensing*, 65(5):611–622.

Malila, W.A., 1980. Change vector analysis: an approach for detecting forest changes with Landsat, *Proceedings of the Sixth Annual Symposium of Machine Processing of Remotely Sensed Data*, Purdue University, West Lafayette, Indiana, pp. 629–643.

Middlekoop, H., and L. Janssen, 1991. Implementation of temporal relationships in knowledge-based classification of satellite images, *Photogrammetric Engineering & Remote Sensing*, 57(7):937–945.

Moody, A., S. Gopal, and A.H. Strahler, 1996. Artificial neural network response to mixed pixels in coarse-resolution satellite data, *Remote Sensing of Environment*, 58:329–343.

Newkirk, R., and F. Wang, 1990. A common knowledge database for remote sensing and geographic information in a change detection expert system, *Environment and Planning B*, 17:395–404.

Parrott, R., S. Carnevale, and D. Stow, 1996. Updating vector land use inventories using multi-date satellite imagery, *Raster Imagery in Geographic Information Systems*, OnWord Press, Santa Fe, New Mexico, pp. 313–321.

San Diego Association of Governments (SANDAG), 1998. *Regional Infromation System Overview*, **http://www.sandag.cog.ca.us** 63 p.

Spear, Bruce D., and T.R. Lakshmanan, 1998. The role of GIS in transportation planning and analysis, Geographical Systems, 5(1):45–58.

Stopher, P.R., D.T. Hartgen, and Li Yuanjun, 1996. SMART: Simulation model for activities, resources and travel, *Transportation*, 23(3):293–312.

Strahler, A., J. Estes, P. Maynard, F. Mertz, and D. Stow, 1980. Incorporating collateral data in Landsat classification and modeling procedures, *Proceedings of the 14th International Symposium on Remote Sensing of the Environment*, San Jose, Costa Rica, 2:1,009–1,026.

U. S. Department of Transportation Bureau of Transportation Statistics, 1997. *Transportation Statistics Annual Report 1997*, BTS97-S-01, Washington, D.C., p. 306

Wang, F., 1993. A knowledge-based vision system for detecting land changes at urban fringes, *IEEE Transactions on Geoscience and Remote Sensing*, 31(1):136–145.

Welch, R., 1982. Spatial resolution requirements for urban studies, *International Journal of Remote Sensing*, 3:139–146.

Westmoreland, S., and D. Stow, 1992. Category identification of changed land-use polygons in an integrated image processing/ geographic information system, *Photogrammetric Engineering & Remote Sensing*, 58(11):1593–1599.

Wrigley, N., 1985. *Categorical Data Analysis for Geographers and Environmental Scientists*, Longman, New York, 392 p.

Zhu, A.-X., 1997. Measuring uncertainty in class assignment for natural resource maps under fuzzy logic, *Photogrammetric Engineering & Remote Sensing*, 63(10):1195–1202.