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Change detection techniques

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Abstract. Timely and accurate change detection of Earth's surface features is extremely important for understanding relationships and interactions between human and natural phenomena in order to promote better decision making. Remote sensing data are primary sources extensively used for change detection in recent decades. Many change detection techniques have been developed. This paper summarizes and reviews these techniques. Previous literature has shown that image differencing, principal component analysis and post-classification comparison are the most common methods used for change detection. In recent years, spectral mixture analysis, artificial neural networks and integration of geographical information system and remote sensing data have become important techniques for change detection applications. Different change detection algorithms have their own merits and no single approach is optimal and applicable to all cases. In practice, different algorithms are often compared to find the best change detection results for a specific application. Research of change detection techniques is still an active topic and new techniques are needed to effectively use the increasingly diverse and complex remotely sensed data available or projected to be soon available from satellite and airborne sensors. This paper is a comprehensive exploration of all the major change detection approaches implemented as found in the literature.

Abbreviations used in this paper

6S	second simulation of the satellite signal in the solar spectrum
ANN	artificial neural networks
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
CVA	change vector analysis
EM	expectation–maximization algorithm
ERS-1	Earth Resource Satellite-1
ETM+	Enhanced Thematic Mapper Plus, Landsat 7 satellite image
GIS	Geographical Information System

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GS	Gramm–Schmidt transformation
J-M distance	Jeffries–Matusita distance
KT	Kauth–Thomas transformation or tasselled cap transformation
LSMA	linear spectral mixture analysis
LULC	land use and land cover
MODIS	Moderate Resolution Imaging Spectroradiometer
MSAVI	Modified Soil Adjusted Vegetation Index
MSS	Landsat Multi-Spectral Scanner image
NDMI	Normalized Difference Moisture Index
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
PCA	principal component analysis
RGB	red, green and blue colour composite
RTB	ratio of tree biomass to total aboveground biomass
SAR	synthetic aperture radar
SAVI	Soil Adjusted Vegetation Index
SPOT HRV	Satellite Probatoire d’Observation de la Terre (SPOT) high resolution visible image
TM	Thematic Mapper
VI	Vegetation Index

1. Introduction

Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times (Singh 1989). Timely and accurate change detection of Earth’s surface features provides the foundation for better understanding relationships and interactions between human and natural phenomena to better manage and use resources. In general, change detection involves the application of multi-temporal datasets to quantitatively analyse the temporal effects of the phenomenon. Because of the advantages of repetitive data acquisition, its synoptic view, and digital format suitable for computer processing, remotely sensed data, such as Thematic Mapper (TM), Satellite Probatoire d’Observation de la Terre (SPOT), radar and Advanced Very High Resolution Radiometer (AVHRR), have become the major data sources for different change detection applications during the past decades. Ten aspects of change detection applications using remote sensing technologies are summarized:

- (1) land-use and land-cover (LULC) change (Gautam and Chennaiah 1985, Gupta and Munshi 1985a, Milne and O’Neill 1990, Csaplovics 1992, Fung 1992, Ram and Kolarkar 1993, Rignot and Vanzyl 1993, Green *et al.* 1994, Adams *et al.* 1995, Hall *et al.* 1995, Salem *et al.* 1995, Dimiyati *et al.* 1996, Bruzzone and Serpico 1997a, b, Rees and Williams 1997, Kwarteng and Chavez 1998, Prakash and Gupta 1998, Ridd and Liu 1998, Roberts *et al.* 1998, Sommer *et al.* 1998, Yuan and Elvidge 1998, Abuelgasim *et al.* 1999, Bryant and Gilvear 1999, Dai and Khorram 1999, Morisette *et al.* 1999, Sohl 1999, Borak *et al.* 2000, Morisette and Khorram 2000, Perakis *et al.* 2000, Tappan *et al.* 2000, Zhan *et al.* 2000, Kaufmann and Seto 2001, Zomer *et al.* 2001, Lunetta *et al.* 2002, Read and Lam 2002, Weng 2002);
- (2) forest or vegetation change (Gupta and Munshi 1985b, Allum and Dreisinger 1987, Graetz *et al.* 1988, Vogelmann 1988, Franklin and Wilson 1991, Cihlar *et al.* 1992, Sader and Winne 1992, Alwashe and Bokhari 1993, Chavez and Mackinnon 1994, Mishra *et al.* 1994, Coppin and Bauer 1995, Olsson 1995, Townshend and Justice 1995, Mouat and Lancaster

- 1996, Batista *et al.* 1997, Islam *et al.* 1997, Yool *et al.* 1997, Chen *et al.* 1998, Hame *et al.* 1998, Jano *et al.* 1998, Grover *et al.* 1999, Salami 1999, Salami *et al.* 1999, Sader *et al.* 2001, Woodcock *et al.* 2001, Lu *et al.* 2002);
- (3) forest mortality, defoliation and damage assessment (Nelson 1983, Leckie 1987, Vogelmann and Rock 1988, Vogelmann 1989, Price *et al.* 1992, Collins and Woodcock 1994, 1996, Macomber and Woodcock 1994, Muchoney and Haack 1994, Gopal and Woodcock 1996, 1999, Royle and Lathrop 1997, Radeloff *et al.* 1999, Rigina *et al.* 1999);
 - (4) deforestation, regeneration and selective logging (Richards 1984, Nelson *et al.* 1987, Lucas *et al.* 1993, 2000, 2002, Durrieu and Deshayes 1994, Franklin *et al.* 1994, Moran *et al.* 1994, Conway *et al.* 1996, Prins and Kikula 1996, Varjo and Folving 1997, Ricotta *et al.* 1998, Stone and Lefebvre 1998, Alves *et al.* 1999, Hudak and Wessman 2000, Souza and Barreto 2000, Tucker and Townshend 2000, Hayes and Sader 2001, Alves 2002, Asner *et al.* 2002, Wilson and Sader 2002);
 - (5) wetland change (Christensen *et al.* 1988, Jensen *et al.* 1993, Ramsey and Laine 1997, Elvidge *et al.* 1998a, Ramsey 1998, Houhoulis and Michener 2000, Kushwaha *et al.* 2000, Munyati 2000);
 - (6) forest fire (Elvidge *et al.* 1998b, Fuller 2000, Cuomo *et al.* 2001) and fire-affected area detection (Jakubauskas *et al.* 1990, Shimabukuro *et al.* 1991, Siljestrom and Moreno-Lopez 1995, Garcia-Haro *et al.* 2001, Rogan and Yool 2001, Bourgeau-Chavez *et al.* 2002);
 - (7) landscape change (Zheng *et al.* 1997, Cushman and Wallin 2000, Franklin *et al.* 2000, Kepner *et al.* 2000, Peralta and Mather 2000, Taylor *et al.* 2000);
 - (8) urban change (Quarmby and Cushnie 1989, Li and Yeh 1998, Ridd and Liu 1998, Ward *et al.* 2000, Chan *et al.* 2001, Yeh and Li 2001, Liu and Lathrop 2002, Prol-Ledesma *et al.* 2002, Yang and Lo 2002, Zhang *et al.* 2002);
 - (9) environmental change (Howarth and Wickware 1981, Jacobberger-Jellison 1994, Armour *et al.* 1998, Schmidt and Glaesser 1998), drought monitoring (Peters *et al.* 2002), flood monitoring (Zhou *et al.* 2000, Dhakal *et al.* 2002, Liu *et al.* 2002), monitoring coastal marine environments (Michalek *et al.* 1993), desertification (Singh *et al.* 1990) and detection of landslide areas (Kimura and Yamaguchi 2000); and
 - (10) other applications such as crop monitoring (Manavalan *et al.* 1995), shifting cultivation monitoring (Dwivedi and Sankar 1991), road segments (Agouris *et al.* 2001) and change in glacier mass balance and facies (Engeset *et al.* 2002).

A variety of change detection techniques have been developed, and many have been summarized and reviewed (Singh 1989, Mouat *et al.* 1993, Deer 1995, Coppin and Bauer 1996, Jensen 1996, Jensen *et al.* 1997, Yuan *et al.* 1998, Serpico and Bruzzone 1999). Due to the importance of monitoring change of Earth's surface features, research of change detection techniques is an active topic, and new techniques are constantly developed. For example, spectral mixture analysis (Adams *et al.* 1995, Roberts *et al.* 1998, Ustin *et al.* 1998), the Li-Strahler canopy model (Macomber and Woodcock 1994), Chi-square transformation (Ridd and Liu 1998), fuzzy sets (Metternicht 1999, 2001), artificial neural networks (ANN) (Gopal and Woodcock 1996, 1999, Abuelgasim *et al.* 1999, Dai and Khorram 1999) and

integration of multi-source data (Petit and Lambin 2001) have been used for change detection applications.

Good change detection research should provide the following information: (1) area change and change rate; (2) spatial distribution of changed types; (3) change trajectories of land-cover types; and (4) accuracy assessment of change detection results. When implementing a change detection project, three major steps are involved: (1) image preprocessing including geometrical rectification and image registration, radiometric and atmospheric correction, and topographic correction if the study area is in mountainous regions; (2) selection of suitable techniques to implement change detection analyses; and (3) accuracy assessment. The accuracies of change detection results depend on many factors, including:

- (1) precise geometric registration between multi-temporal images,
- (2) calibration or normalization between multi-temporal images,
- (3) availability of quality ground truth data,
- (4) the complexity of landscape and environments of the study area,
- (5) change detection methods or algorithms used,
- (6) classification and change detection schemes,
- (7) analyst's skills and experience,
- (8) knowledge and familiarity of the study area, and
- (9) time and cost restrictions.

Because of the impacts of complex factors, different authors often arrived at different and sometimes controversial conclusions about which change detection techniques are most effective. In practice, it is not easy to select a suitable algorithm for a specific change detection project. Hence, a review of change detection techniques used in previous research and applications is useful to understand how these techniques can be best used to help address specific problems. When study areas and image data are selected for research, identifying a suitable change detection technique becomes of great significance in producing good quality change detection results.

This paper summarizes change detection techniques, reviews their applications, and provides recommendations for selection of suitable change detection methods. This paper is organized into eight sections as follows: §1 gives a brief introduction to applications of change detection techniques; §2 discusses considerations before implementing change detection analyses; §3 summarizes and reviews seven categories of change detection techniques; §4 provides a review of comparative analyses among the different techniques; §5 briefly reviews global change analyses using coarse resolution satellite data; §6 discusses selection of thresholds; §7 discusses accuracy assessment; and §8 provides a summary and recommendations.

2. Considerations before implementing change detection

MacLeod and Congalton (1998) described four important aspects of change detection for monitoring natural resources: detecting if a change has occurred, identifying the nature of the change, measuring the areal extent of the change, and assessing the spatial pattern of the change. Lambin and Strahler (1994b) listed five categories of causes that influenced land-cover change: long-term natural changes in climate conditions; geomorphological and ecological processes such as soil erosion and vegetation succession; human-induced alterations of vegetation cover and landscapes such as deforestation and land degradation; inter-annual climate variability; and the greenhouse effect caused by human activities. Successfully

implementing a change detection analysis using remotely sensed data requires careful considerations of the remote sensor system, environmental characteristics and image processing methods. The temporal, spatial, spectral and radiometric resolutions of remotely sensed data have a significant impact on the success of a remote sensing change detection project. The important environmental factors include atmospheric conditions, soil moisture conditions and phenological characteristics (Jensen 1996, Weber 2001).

Of the various requirements of preprocessing for change detection, multi-temporal image registration and radiometric and atmospheric corrections are the most important. The importance of accurate spatial registration of multi-temporal imagery is obvious because largely spurious results of change detection will be produced if there is misregistration (Townshend *et al.* 1992, Dai and Khorram 1998, Stow 1999, Verbyla and Boles 2000, Carvalho *et al.* 2001, Stow and Chen 2002). Conversion of digital numbers to radiance or surface reflectance is a requirement for quantitative analyses of multi-temporal images. A variety of methods, such as relative calibration, dark object subtraction, and second simulation of the satellite signal in the solar spectrum (6S), have been developed for radiometric and atmospheric normalization or correction (Markham and Barker 1987, Gilabert *et al.* 1994, Chavez 1996, Stefan and Itten 1997, Vermote *et al.* 1997, Tokola *et al.* 1999, Heo and FitzHugh 2000, Yang and Lo 2000, Song *et al.* 2001, Du *et al.* 2002, McGovern *et al.* 2002). If the study area is rugged or mountainous, topographic correction may be necessary. More detailed information about topographic correction can be found in Teillet *et al.* (1982), Civco (1989), Colby (1991) and Meyer *et al.* (1993).

Before implementing change detection analysis, the following conditions must be satisfied: (1) precise registration of multi-temporal images; (2) precise radiometric and atmospheric calibration or normalization between multi-temporal images; (3) similar phenological states between multi-temporal images; and (4) selection of the same spatial and spectral resolution images if possible. Many kinds of remote sensing data are available for change detection applications. Historically, Landsat Multi-Spectral Scanner (MSS), TM, SPOT, AVHRR, radar and aerial photographs are the most common data sources, but new sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) are becoming important. When selecting remote sensing data for change detection applications, it is important to use the same sensor, same radiometric and spatial resolution data with anniversary or very near anniversary acquisition dates in order to eliminate the effects of external sources such as Sun angle, seasonal and phenological differences. A more detailed description about these considerations before implementing change detection can be found in Coppin and Bauer (1996), Jensen (1996) and Biging *et al.* (1999).

Determination of change direction is also important in selecting appropriate change detection techniques. Some techniques such as image differencing can only provide change/non-change information, while some techniques such as post-classification comparison can provide a complete matrix of change directions. For a given research purpose, when the remotely sensed data and study areas are identified, selection of an appropriate change detection method has considerable significance in producing a high-quality change detection product.

3. A review of change detection techniques

The objective of change detection is to compare spatial representation of two points in time by controlling all variances caused by differences in variables that are not of interest and to measure changes caused by differences in the variables of interest (Green *et al.* 1994). The basic premise in using remotely sensed data for change detection is that changes in the objects of interest will result in changes in reflectance values or local textures that are separable from changes caused by other factors such as differences in atmospheric conditions, illumination and viewing angles, and soil moistures (Deer 1995). Because digital change detection is affected by spatial, spectral, thematic and temporal constraints, and because many change detection techniques are possible to use, the selection of a suitable method or algorithm for a given research project is important, but not easy.

For the sake of convenience, the change detection methods are grouped into seven categories: (1) algebra, (2) transformation, (3) classification, (4) advanced models, (5) Geographical Information System (GIS) approaches, (6) visual analysis, and (7) other approaches. For the first six categories, the main characteristics, advantages and disadvantages, key factors affecting change detection results, and some application examples are provided in table 1. The level of complexity for each change detection technique is ranked. The seventh category includes those change detection techniques that are not suitable to group into any one of the six categories and are not yet extensively used in practice. Hence, this category is not discussed in detail. The majority of these techniques are used for change detection with relatively fine spatial resolution such as Landsat MSS, TM, SPOT, or radar.

3.1. Algebra

The algebra category includes image differencing, image regression, image ratioing, vegetation index differencing, change vector analysis (CVA) and background subtraction. These algorithms have a common characteristic, i.e. selecting thresholds to determine the changed areas. These methods (excluding CVA) are relatively simple, straightforward, easy to implement and interpret, but these cannot provide complete matrices of change information. CVA is a conceptual extension of image differencing. This approach can detect all changes greater than the identified thresholds and can provide detailed change information. One disadvantage of the algebra category is the difficulty in selecting suitable thresholds to identify the changed areas. In this category, two aspects are critical for the change detection results: selecting suitable image bands or vegetation indices and selecting suitable thresholds to identify the changed areas.

Angelici *et al.* (1977) used the difference of band ratio data and a threshold technique to identify changed areas. Jensen and Toll (1982) found the usefulness of visible red band data in change detection analysis in both vegetated and urban environments. Chavez and Mackinnon (1994) also indicated that red band image differencing provided better vegetation change detection results than using Normalized Difference Vegetation Index (NDVI) in arid and semi-arid environments of the south-western United States. Pilon *et al.* (1988) concluded that visible red band data provided the most accurate identification of spectral change for their semi-arid study area of north-western Nigeria in sub-Saharan Africa. Ridd and Liu (1998) compared image differencing, regression method, Kauth–Thomas transformation or tasselled cap transformation (KT), and Chi-square transformation for urban land-use change detection in the Salt Lake Valley area using Landsat TM

Table 1. Summary of change detection techniques. (The five levels indicate the complexity of the change detection techniques, from simplest 1 to the most complex 5.)

Techniques	Characteristics	Advantages	Disadvantages	Examples	Level	Key factors
Category I. Algebra						
1. Image differencing	Subtracts the first-date image from a second-date image, pixel by pixel	Simple and straightforward, easy to interpret the results	Cannot provide a detailed change matrix, requires selection of thresholds	Forest defoliation (Muchoney and Haack 1994), land-cover change (Sohl 1999) and irrigated crops monitoring (Manavalan <i>et al.</i> 1995)	1	Identifies suitable image bands and thresholds
2. Image regression	Establishes relationships between bi-temporal images, then estimates pixel values of the second-date image by use of a regression function, subtracts the regressed image from the first-date image	Reduces impacts of the atmospheric, sensor and environmental differences between two-date images	Requires to develop accurate regression functions for the selected bands before implementing change detection	Tropical forest change (Singh 1986) and forest conversion (Jha and Unni 1994).	1	Develops the regression function; identifies suitable bands and thresholds
3. Image ratioing	Calculates the ratio of registered images of two dates, band by band	Reduces impacts of Sun angle, shadow and topography	Non-normal distribution of the result is often criticized	Land-use mapping and change detection (Prakash and Gupta 1998)	1	Identifies the image bands and thresholds

Table 1. (Continued)

Techniques	Characteristics	Advantages	Disadvantages	Examples	Level	Key factors
4. Vegetation index differencing	Produces vegetation index separately, then subtracts the second-date vegetation index from the first-date vegetation index	Emphasizes differences in the spectral response of different features and reduces impacts of topographic effects and illumination	Enhances random noise or coherence noise	Vegetation change (Townshend and Justice 1995, Guerra <i>et al.</i> 1998, Lyon <i>et al.</i> 1998) and forest canopy change (Nelson 1983)	1	Identifies suitable vegetation index and thresholds
5. Change vector analysis (CVA)	Generates two outputs: (1) the spectral change vector describes the direction and magnitude of change from the first to the second date; and (2) the total change magnitude per pixel is computed by determining the Euclidean distance between end points through <i>n</i> -dimensional change space	Ability to process any number of spectral bands desired and to produce detailed change detection information	Difficult to identify land cover change trajectories	Change detection of landscape variables (Lambin 1996), land-cover changes (Johnson and Kasischke 1998), disaster assessment (Johnson 1994, Schoppmann and Tyler 1996), and conifer forest change (Cohen and Fiorella 1998, Allen and Kupfer 2000)	3	Defines thresholds and identifies change trajectories

6. Background subtraction	Non-change areas have slowly varying background grey levels. A low-pass filtered variant of the original image is used to approximate the variations to the background image. A new image is produced through subtracting the background image from the original image	Easy to implement	Low accuracy	Tropical forest change (Singh 1989).	1	Develops the background image
Category II. Transformation						
7. Principal component analysis (PCA)	Assumes that multi-temporal data are highly correlated and change information can be highlighted in the new components. Two ways to apply PCA for change detection are: (1) put two or more dates of images into a single file, then perform PCA and analyse the minor component images for change information; and (2) perform PCA separately, then subtract the second-date PC image from the corresponding	Reduces data redundancy between bands and emphasizes different information in the derived components	PCA is scene dependent, thus the change detection results between different dates are often difficult to interpret and label. It cannot provide a complete matrix of change class information and requires determining thresholds to identify the changed areas	Land-cover change (Byrne <i>et al.</i> 1980, Ingebritsen and Lyon 1985, Parra <i>et al.</i> 1996, Kwarteng and Chavez 1998), urban expansion (Li and Yeh 1998), tropical forest conversion (Jha and Unni 1994), forest mortality (Collins and Woodcock 1996) and forest defoliation (Muchoney and Haack 1994)	2	Analyst's skill in identifying which component best represents the change and selecting thresholds

Table 1. (Continued)

Techniques	Characteristics	Advantages	Disadvantages	Examples	Level	Key factors
8. Tasselled cap (KT)	PC image of the first date The principle of this method is similar to PCA. The only difference from PCA is that PCA depends on the image scene, and KT transformation is independent of the scene. The change detection is implemented based on the three components: brightness, greenness and wetness	Reduces data redundancy between bands and emphasizes different information in the derived components. KT is scene independent.	Difficult to interpret and label change information, cannot provide a complete change matrix; requires determining thresholds to identify the changed areas. Accurate atmospheric calibration for each date of image is required	Monitoring forest mortality (Collins and Woodcock 1996), monitoring green biomass change (Coppin <i>et al.</i> 2001) and land-use change (Seto <i>et al.</i> 2002)	2	Analyst's skill is needed in identifying which component best represents the change and selecting thresholds
9. Gramm–Schmidt (GS)	The GS method orthogonalizes spectral vectors taken directly from bi-temporal images, as does the original KT method, produces three stable components corresponding to multi-temporal analogues of KT brightness, greenness and wetness, and a change component	The association of transformed components with scene characteristics allows the extraction of information that would not be accessible using other change detection techniques	It is difficult to extract more than one single component related to a given type of change. The GS process relies on selection of spectral vectors from multi-date image typical of the type of change being examined	Monitoring forest mortality (Collins and Woodcock 1994, 1996)	3	Initial identification of the stable subspace of the multi-date data is required

10. Chi-square	$Y = (X - M)^T \Sigma^{-1} \times (X - M)$ <p>Y: digital value of change image, X: vector of the difference of the six digital values between the two dates, M: vector of the mean residuals of each band, T: transverse of the matrix, Σ^{-1}: inverse covariance matrix of the six bands</p>	Multiple bands are simultaneously considered to produce a single change image.	The assumption that a value of $Y=0$ represents a pixel of no change is not true when a large portion of the image is changed. Also the change related to specific spectral direction is not readily identified	Urban environmental change (Ridd and Liu 1998)	3	Y is distributed as a Chi-square random variable with p degrees of freedom (p is the number of bands)
Category III. Classification						
11. Post-classification comparison	Separately classifies multi-temporal images into thematic maps, then implements comparison of the classified images, pixel by pixel	Minimizes impacts of atmospheric, sensor and environmental differences between multi-temporal images; provides a complete matrix of change information	Requires a great amount of time and expertise to create classification products. The final accuracy depends on the quality of the classified image of each date	LULC change (Brondízio <i>et al.</i> 1994, Dimyati <i>et al.</i> 1996, Mas 1997, Castelli <i>et al.</i> 1998, Miller <i>et al.</i> 1998, Mas 1999, Foody 2001), wetland change (Jensen <i>et al.</i> 1987, 1995, Munyati 2000) and urban expansion (Ward <i>et al.</i> 2000)	2	Selects sufficient training sample data for classification

Table 1. (Continued)

Techniques	Characteristics	Advantages	Disadvantages	Examples	Level	Key factors
12. Spectral–temporal combined analysis	Puts multi-temporal data into a single file, then classifies the combined dataset and identifies and labels the changes	Simple and time-saving in classification	Difficult to identify and label the change classes; cannot provide a complete matrix of change information	Changes in coastal zone environments (Weismiller <i>et al.</i> 1977) and forest change (Soares and Hoffer 1994)	3	Labels the change classes
13. EM detection	The EM detection is a classification-based method using an expectation–maximization (EM) algorithm to estimate the <i>a priori</i> joint class probabilities at two times. These probabilities are estimated directly from the images under analysis	This method was reported to provide higher change detection accuracy than other change detection methods	Requires estimating the <i>a priori</i> joint class probability.	Land-cover change (Bruzzone and Serpico 1997b, Serpico and Bruzzone 1999)	3	Estimates the <i>a priori</i> joint class probability
14. Unsupervised change detection	Selects spectrally similar groups of pixels and clusters date 1 image into primary clusters, then labels spectrally similar groups in date 2 image into primary clusters in date 2 image, and finally detects and	This method makes use of the unsupervised nature and automation of the change analysis process	Difficulty in identifying and labelling change trajectories	Forest change (Hame <i>et al.</i> 1998)	3	Identifies the spectrally similar or relatively homogeneous units

15. Hybrid change detection	identifies changes and outputs results Uses an overlay enhancement from a selected image to isolate changed pixels, then uses supervised classification. A binary change mask is constructed from the classification results. This change mask sieves out the changed themes from the LULC maps produced for each date	This method excludes unchanged pixels from classification to reduce classification errors	Requires selection of thresholds to implement classification; somewhat complicated to identify change trajectories	LULC change (Pilon <i>et al.</i> 1988, Luque 2000), vegetation change (Petit <i>et al.</i> 2001) and monitoring eelgrass (MacLeod and Congalton 1998)	3	Selects suitable thresholds to identify the change and non-change areas and develops accurate classification results.
16. Artificial neural networks (ANN)	The input used to train the neural network is the spectral data of the period of change. A back-propagation algorithm is often used to train the multi-layer perceptron neural network model	ANN is a non-parametric supervised method and has the ability to estimate the properties of data based on the training samples	The nature of hidden layers is poorly known; a long training time is required. ANN is often sensitive to the amount of training data used. ANN functions are not common in image processing software	Mortality detection in Lake Tahoe Basin, California (Gopal and Woodcock 1996, 1999), land-cover change (Abuelgasim <i>et al.</i> 1999, Dai and Khorram 1999), forest change (Woodcock <i>et al.</i> 2001) urban change (Liu and Lathrop 2002)	5	The architecture used such as the number of hidden layers, and training samples

Table 1. (Continued)

Techniques	Characteristics	Advantages	Disadvantages	Examples	Level	Key factors
Category IV. Advanced models						
17. Li–Strahler reflectance model	The Li–Strahler canopy model is used to estimate each conifer stand crown cover for two dates of imageries separately. Comparison of the stand crown covers for two dates is conducted to produce the change detection results	This method combines the techniques of digital image processing of remotely sensed data with traditional sampling and field observation methods. It provides statistical results and maps showing the geometric distribution of changed patterns	This method requires a large number of field measurement data. It is complex and not available in commercial image processing software. It is only suitable for vegetation change detection	Mapping and monitoring conifer mortality (Macomber and Woodcock 1994)	5	Develops the stand crown cover images and identifies the crown characteristics of vegetation types
18. Spectral mixture model	Uses spectral mixture analysis to derive fraction images. Endmembers are selected from training areas on the image or from spectra of materials occurring in the study area or from a relevant spectral library. Changes are detected by comparing the ‘before’ and ‘after’	The fractions have biophysical meanings, representing the areal proportion of each endmember within the pixel. The results are stable, accurate and repeatable	This method is regarded as an advanced image processing analysis and is somewhat complex	Land-cover change in Amazonia (Adams <i>et al.</i> 1995, Roberts <i>et al.</i> 1998), seasonal vegetation patterns using AVIRIS data (Ustin <i>et al.</i> 1998) and vegetation	5	Identifies suitable endmembers; defines suitable thresholds for each land-cover class based on fractions

	fraction images of each endmember. The quantitative changes can be measured by classifying images based on the endmember fractions			change using TM data (Rogan <i>et al.</i> 2002)	
19. Biophysical parameter method	Develops a biophysical parameter estimation model through integration of field measurements and remotely sensed data and estimates the parameter for the study area. The vegetation types are classified based on the biophysical parameter. The model is also transferred to other image data with different dates to estimate the selected parameters after reflectance calibration or normalization. Change detection is implemented through comparing the biophysical parameters	This method can accurately detect vegetation change based on vegetation physical structures	Requires great effort to develop the model and implement accurate image calibration to eliminate the difference in reflectance caused by different atmospheric and environmental conditions. Requires a large number of field measurement data. The method is only suitable for vegetation change detection	Tropical successional forest detection in Amazon basin (Lu 2001, Lu <i>et al.</i> 2002)	5 Develops relevant models for estimation of biophysical parameters and defines each vegetation class based on biophysical parameters

Table 1. (Continued)

Techniques	Characteristics	Advantages	Disadvantages	Examples	Level	Key factors
Category V. GIS						
20. Integrated GIS and remote sensing method	Incorporates image data and GIS data, such as the overlay of GIS layers directly on image data; moves results of image processing into GIS system for further analysis	Allows access of ancillary data to aid interpretation and analysis and has the ability to directly update land-use information in GIS	Different data quality from various sources often degrades the results of LULC change detection	LULC (Price <i>et al.</i> 1992, Westmoreland and Stow 1992, Mouat and Lancaster 1996, Slater and Brown 2000, Petit and Lambin 2001, Chen 2002, Weng 2002) and urban sprawl (Yeh and Li 2001, Prol-Ledesma <i>et al.</i> 2002)	4	The accuracy of different data sources and their registration accuracies between the thematic images
21. GIS approach	Integrates past and current maps of land use with topographic and geological data. The image overlaying and binary masking techniques are useful in revealing quantitatively the change dynamics in each category	This method allows incorporation of aerial photographic data of current and past land-use data with other map data	Different GIS data with different geometric accuracy and classification system degrades the quality of results	Urban change (Lo and Shipman 1990) and landscape change (Taylor <i>et al.</i> 2000)	4	The accuracy of different data sources and their registration accuracies between the thematic images

Category VI. Visual analysis

22. Visual interpretation	One band (or VI) from date1 image as red, the same band (or VI) from date2 image as green, and the same band (or VI) from date3 image as blue if available. Visually interprets the colour composite to identify the changed areas. An alternative is to implement on-screen digitizing of changed areas using visual interpretation based on overlaid images of different dates	Human experience and knowledge are useful during visual interpretation. Two or three dates of images can be analysed at one time. The analyst can incorporate texture, shape, size and patterns into visual interpretation to make a decision on the LULC change	Cannot provide detailed change information. The results depend on the analyst's skill in image interpretation. Time-consuming and difficulty in updating the results	Land-use change (Sunar 1998, Ulbricht and Heckendorff 1998), forest change (Sader and Winne 1992), monitoring selectively logged areas (Stone and Lefebvre 1998, Asner <i>et al.</i> 2002) and land-cover change (Slater and Brown 2000)	1	Analyst's skill and familiarity with the study area
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Category VII. Other change detection techniques

- 23. Measures of spatial dependence (Henebry 1993)
- 24. Knowledge-based vision system (Wang 1993)
- 25. Area production method (Hussin *et al.* 1994)
- 26. Combination of three indicators: vegetation indices, land surface temperature, and spatial structure (Lambin and Strahler 1994b)
- 27. Change curves (Lawrence and Ripple 1999)
- 28. Generalized linear models (Morissette *et al.* 1999)
- 29. Curve-theorem-based approach (Yue *et al.* 2002)
- 30. Structure-based approach (Zhang *et al.* 2002)
- 31. Spatial statistics-based method (Read and Lam 2002)

data. They concluded that band TM 3 differencing and its regression were the best methods; however, none of the algorithms or band selections used was absolutely superior to the others.

Nelson (1983) examined the utility of image differencing, image ratioing and vegetation index differencing in detecting gypsy moth defoliation and found that a difference of the MSS7/MSS5 ratio was more useful in delineation of defoliated area than any single band-pair difference or ratio. Stow *et al.* (1990) found that ratioing multi-sensor, multi-temporal satellite image data produced higher change detection accuracy than did principal component analysis (PCA) and was useful as a land-use change enhancement technique. Ratioing red and near-infrared bands of a Landsat MSS–SPOT high resolution visible image (HRV) (XS) multi-temporal pair produced substantially higher change detection accuracy (about 10% better) than ratioing similar bands of a Landsat MSS–Landsat TM multi-temporal pair. Prakash and Gupta (1998) used image differencing, image ratioing and NDVI differencing to detect land-use changes in a coral mining area of India and found that no significant difference existed among these methods in detecting land-use change in this study and each method had its own merit. Lyon *et al.* (1998) compared seven vegetation indices from three different dates of MSS data for land-cover change detection and concluded that NDVI differencing technique demonstrated the best vegetation change detection. Sohl (1999) reviewed and evaluated five methods: univariate image differencing, an ‘enhanced’ image differencing, vegetation index differencing, post-classification differencing and CVA, and concluded that CVA excelled at providing rich qualitative details about the nature of a change. Hayes and Sader (2001) compared NDVI differencing, PCA, and red, green and blue colour composite (RGB)–NDVI for detection of tropical forest clearing and vegetation regrowth in Guatemala’s Maya Biosphere Reserve and found that the RGB–NDVI method produced the highest overall accuracy (85%).

In the algebra-based change detection category, image differencing is the most often used change detection method in practice. Visible red band image differencing has shown to be suitable for change detection in semi-arid and arid environments, but it is not clear that this is true in other environments such as moist tropical regions. Different authors have arrived at different conclusions about which method provided the best results among the image ratioing, vegetation index differencing, image regression, and CVA approaches, since results vary depending on the characteristics of the study areas and image data used. The background subtraction method was not often used due to its poor change detection capability.

3.2. Transformation

The transformation category includes PCA, KT, Gramm–Schmidt (GS), and Chi-square transformations. One advantage of these methods is in reducing data redundancy between bands and emphasizing different information in derived components. However, they cannot provide detailed change matrices and require selection of thresholds to identify changed areas. Another disadvantage is the difficulty in interpreting and labelling the change information on the transformed images.

Fung and LeDrew (1987) used PCA and differences in KT transformation images to detect land-cover changes from multi-temporal MSS and TM images and concluded that differencing greenness and brightness images from the KT

transformation of MSS and TM data was most appropriate for detecting land-cover changes from multi-sensor data. In another study, Fung (1990) examined image differencing, PCA and KT transformation for land-cover change detection and found that images associated with changes in the near-infrared reflectance or greenness could detect crop type change and changes between vegetative and non-vegetative features. Guirguis *et al.* (1996) compared standardized and unstandardized PCA, image differencing, and ratioing. They found that standardized PCA was more capable of identifying changes. Other studies also agreed that standardized PCA was more reliable in change detection than unstandardized PCA (Singh and Harrison 1985, Fung and LeDrew 1987, Eklundh and Singh 1993).

Sunar (1998) compared image overlay, image differencing, PCA and post-classification comparison for land-cover change detection in the Ikitelli area, Istanbul, Turkey, and found that PCA and post-classification comparison highlighted differences attributed to changes, but each of the methods used has some merit with regard to the information contents or interpretability. Collins and Woodcock (1996) used linear change detection techniques for mapping forest mortality using Landsat TM data and found that PCA and multi-temporal KT transformation were better than the GS orthogonalization process and that changes in KT wetness were the most reliable single indicators of forest change. Rogan and Yool (2001) compared vegetation indices (NDVI, Soil Adjusted Vegetation Index (SAVI), Modified Soil Adjusted Vegetation Index (MSAVI) and band ratio TM 7/4), PCA, and KT components and found that the KT approach provided best detection results of fire-induced vegetation depletion in the Peloncillo Mountains, Arizona and New Mexico, with an overall kappa of 0.66.

In order to improve change detection accuracy, different change detection techniques can be combined. For example, Gong (1993) used band-pair image differencing for each spectral band, then used PCA for the multi-spectral difference image, and finally applied fuzzy operations to combine change information in different change component images into a single image. This method was shown to provide better change detection results than simple image differencing. Coppin and Bauer (1994) examined forest change detection by a comparison of vegetation indices for different dates of imageries. The vegetation indices included brightness, greenness and wetness from the KT transformation, as well as NDVI, green ratios and mid-infrared ratios. Then Jeffries–Matusita distance (J-M distance) was used for optimal feature selection. It was found that changes in brightness and greenness identified the most important forest canopy change features and that these can be adequately expressed as a normalized difference or a second principal component.

In the transformation category, PCA and KT are most often used approaches for detecting change/non-change information. The KT method seems useful in many change detection applications. One advantage of KT transformation over PCA is that KT transform coefficients are independent of the image scenes, while PCA is dependent on the image scenes. The GS and Chi-square methods are relatively less frequently used in practice due to their relative complexity compared to PCA and KT transforms. Also GS and Chi-square methods are not available in most of the commercial remote sensing image processing software.

3.3. Classification

The classification category includes post-classification comparison, spectral-temporal combined analysis, expectation-maximization algorithm (EM) change

detection, unsupervised change detection, hybrid change detection, and ANN. These methods are based on the classified images, in which the quality and quantity of training sample data are crucial to produce good quality classification results. The major advantage of these methods is the capability of providing a matrix of change information and reducing external impact from atmospheric and environmental differences between the multi-temporal images. However, selecting high-quality and sufficiently numerous training sample sets for image classification is often difficult, in particular for historical image data classification. The time-consuming and difficult task of producing highly accurate classifications often leads to unsatisfactory change detection results, especially when high-quality training sample data are not available.

Li and Yeh (1998) found that PCA of stacked multi-temporal images combined with supervised maximum likelihood classification can effectively monitor urban land-use change in the Pearl River Delta. Silapaswan *et al.* (2001) used CVA, unsupervised classification, and visual interpretation of aerial photographs to detect land-cover change and found that the combination of CVA and unsupervised classification provided more powerful interpretation of change than either method alone. Petit *et al.* (2001) used the combination of image differencing and post-classification to detect detailed 'from-to' land-cover change in south-eastern Zambia and such a hybrid change detection method was regarded as better than post-classification comparison techniques. Foody (2001) found that post-classification comparison underestimated the areas of land-cover change, but where the change was detected, it typically overestimated its magnitude. Wilson and Sader (2002) compared multi-temporal classification of the TM NDVI and Normalized Difference Moisture Index (NDMI) for detection of forest harvest type and found that the RGB-NDMI method produced higher accuracies compared to the RGB-NDVI method. Recently, ANN has been used for land-cover change (Abuelgasim *et al.* 1999, Dai and Khorram 1999), forest mortality detection (Gopal and Woodcock 1996, 1999), forest change (Woodcock *et al.* 2001) and urban change (Liu and Lathrop 2002). For example, Liu and Lathrop (2002) applied the ANN approach to detect urban change using multi-temporal TM data and found that the ANN-based method improved accuracy about 20–30% compared to post-classification comparison.

These classification methods often require a large amount of training sample data for supervised or unsupervised classification of image data. Image transformation, vegetation indices, advanced classification methods, modelling, and integration of different data sources are often used to improve classification results. Post-classification comparison is a common approach used for change detection in practice, but the difficulty in classifying historical image data often seriously affects the change detection results. The hybrid change detection method combines the advantages of the threshold and classification methods. The threshold methods such as image differencing are often used to detect the changed areas, then classification methods are used to classify and analyse detected change areas using the threshold method. The spectral-temporal combined change detection method and unsupervised change detection method are used less frequently in practice due to the difficulty in identifying and labelling change trajectories. The EM method is not commonly used due to the complexity of estimating *a priori* joint class probability. The ANN approach can probably provide better change detection results when the land-cover classes are not normally distributed. In recent years, the research on ANN methods for change detection has attracted increasing attention

(Abuelgasim *et al.* 1999, Dai and Khorram 1999, Gopal and Woodcock 1999, Woodcock *et al.* 2001, Liu and Lathrop 2002).

3.4. *Advanced models*

The advanced model-based change detection category includes the Li–Strahler reflectance model, spectral mixture models, and biophysical parameter estimation models. In these methods, the image reflectance values are often converted to physically based parameters or fractions through linear or nonlinear models. The transformed parameters are more intuitive to interpret and better to extract vegetation information than are spectral signatures. The disadvantage of these methods is the time-consuming and difficult process of developing suitable models for conversion of image reflectance values to biophysical parameters.

In this category, linear spectral mixture analysis (LSMA) is the most often used approach for detection of land-cover change (Adams *et al.* 1995, Roberts *et al.* 1998), vegetation change (Ustin *et al.* 1998, Rogan *et al.* 2002), defoliation (Radeloff *et al.* 1999), fire and grazing patterns (Wessman *et al.* 1997), urban area change (Kressler and Steinnocher 1996) and environmental change (Piwowar *et al.* 1998). Adams *et al.* (1995) and Roberts *et al.* (1998) applied LSMA associated with four endmembers (green vegetation, non-photosynthetic vegetation, soil and shade) to analyse the land-cover change in the Brazilian Amazon and regarded this as a better approach than traditional classification and change detection methods. Souza and Barreto (2000) used the LSMA approach to detect the selectively logged forests in the eastern Amazon and found that the soil fraction images derived from LSMA can successfully detect the areas affected by the selective logging. Rogan *et al.* (2002) compared multi-temporal KT and LSMA methods for vegetation change detection using TM images in southern California and found that the LSMA approach provided about 5% higher change detection accuracy than the KT approach. In the LSMA approach, a critical step is to identify suitable endmembers. A detailed description of the LSMA approach and endmember selection can be found in Adams *et al.* (1995), Bateson and Curtiss (1996), Tompkins *et al.* (1997), Roberts *et al.* (1998) and Mustard and Sunshine (1999).

The Li–Strahler canopy model was used to monitor conifer mortality through estimation of each conifer stand crown cover from each date of image, then compared the difference of stand crown cover to produce the change detection results (Macomber and Woodcock 1994). The advantage of this method is the capability to combine the digital image processing method with traditional sampling and field observations-based methods. The difficulty in application of this model is collection of required sufficient field measurements. Also this model is relatively complex and not available for common image processing software.

Lu (2001) found that the ratio of tree biomass to total aboveground biomass (RTB) is a good biophysical parameter for differentiating successional forest stages based on field vegetation inventory data analysis in eastern Amazonia. The RTB parameter reflects vegetation stand structure and regrowth stages. It can be developed through integration of field vegetation inventory data and Landsat TM images (Lu 2001). Hence, the RTB approach can be used to identify vegetation classes. In addition, multi-temporal RTB images have the capability to detect vegetation change after the reflectance differences caused by environmental conditions are calibrated between multi-temporal TM images. This method has

been used for successional and mature forest change detection in the Altamira and Bragantina study areas of the Brazilian Amazon (Lu 2001, Lu *et al.* 2002).

When sufficient field vegetation measurements are available, the Li-Strahler canopy model and the biophysical parameter estimation model are valuable for quantitative detection of vegetation change. However, applications of both models are often time-consuming and difficult. Also they can provide only vegetation change detection and are not suitable for non-vegetation change detection. The LSMA approach has been shown to be powerful for land-cover change detection. A key step in implementing LSMA for change detection is to select suitable endmembers for development of high-quality fraction images and to find proportional compositions of each land-cover class. The big advantage of this approach is its stable, reliable and repeatable extraction of quantitative subpixel information that provides the potential to accurately detect land-cover change.

3.5. GIS

The GIS-based change detection category includes the integrated GIS and remote sensing method and the pure GIS method. The advantage of using GIS is the ability to incorporate different source data into change detection applications. However, different source data associated with different data accuracies and formats often affect the change detection results.

Lo and Shipman (1990) used a GIS approach to assess the impact of new town development in Hong Kong, through integration of multi-temporal aerial photographic data of land use and found that the image overlaying and binary masking techniques were useful in revealing quantitatively the change dynamics in each category of land use. In recent years, incorporation of multi-source data (e.g. aerial photographs, TM, SPOT and previous thematic maps) has become an important method for land-use and land-cover (LULC) change detection (Mouat and Lancaster 1996, Salami 1999, Salami *et al.* 1999, Reid *et al.* 2000, Petit and Lambin 2001, Chen 2002, Weng 2002), especially when the change detection involved long period intervals associated with different data sources, formats and accuracies or multi-scale land-cover change analysis (Petit and Lambin 2001). Weng (2002) used the integration of remote sensing, GIS and stochastic modelling to detect land-use change in the Zhujiang Delta of China and indicated that such integration was an effective approach for analysing the direction, rate and spatial pattern of land-use change. Yang and Lo (2002) used an unsupervised classification approach, GIS-based image spatial reclassification, and post-classification comparison with GIS overlay to map the spatial dynamics of urban land-use/land-cover change in the Atlanta, Georgia, metropolitan area. GIS approaches have shown many advantages over traditional change detection methods in multi-source data analysis.

Most previous applications of GIS approaches in change detection were focused on urban areas. This is probably because traditional change detection methods often have poor change detection results due to the complexity of urban landscapes and these cannot effectively utilize multi-source data analysis. Thus, the powerful GIS functions provide convenient tools for the multi-source data processing and are effective in handling the change detection analysis using multi-source data. More research focusing on integration of GIS and remote sensing techniques is necessary for better implementation of change detection analyses.

3.6. Visual analysis

The visual analysis category includes visual interpretation of multi-temporal image composite and on-screen digitizing of changed areas. This method can make full use of an analyst's experience and knowledge. Texture, shape, size and patterns of the images are key elements useful for identification of LULC change through visual interpretation. These elements are not often used in the digital change detection analysis because of the difficulty in extraction of these elements. However, in visual interpretation, a skilled analyst can incorporate all these elements in helping make decisions about LULC change. The disadvantage of this method is the time consumed for a large-area change detection application and it is difficult to timely update the change detection results. It is also difficult to provide detailed change trajectories.

Visual interpretation was extensively used in different fields such as forest inventory before the 1970s when digital satellite data were not available and the capability of computer techniques and image processing in handling a large amount of data were poor. With the rapid development of computer technologies and remote sensing techniques, digital computer processing gradually replaced the visual interpretation. However, automatic image processing is not always feasible for all cases. For example, detection of forest selective logging or disturbance is often very difficult using computer processing; however, visual interpretation has the potential to identify such changes by skilled analysts. Stone and Lefebvre (1998) used visual interpretation to evaluate selective logging in Para, Brazil, because of the difficulty in automatically detecting the location and extent of logging using computer processing. Loveland *et al.* (2002) used visual interpretation on fine resolution data (MSS, TM and Enhanced Thematic Mapper Plus (ETM+)), combined with sampling design, to detect United States land-cover changes and estimate the change rates. Also visual interpretation of multi-temporal colour composite images is valuable for qualitatively analysing the land-cover change and assisting for the selection of suitable digital change detection methods based on the landscape characteristics of a study area.

3.7. Other change detection techniques

In addition to the six categories of change detection techniques discussed above, there are also some methods that cannot be attributed to one of the categories indicated above and that have not yet frequently been used in practice. For example, Henebry (1993) used measures of spatial dependence with TM data to detect grassland change. Wang (1993) used a knowledge-based vision system to detect land-cover change at urban fringes. Lambin and Strahler (1994b) used three indicators, vegetation indices, land surface temperature and spatial structure, derived from AVHRR, to detect land-cover change in west Africa. Lawrence and Ripple (1999) used change curves and Hussin *et al.* (1994) used an area production model to detect forest cover changes. Morissette *et al.* (1999) used generalized linear models to detect land-cover change. A curve-theorem-based approach was also used for change detection in the Yellow River Delta (Yue *et al.* 2002). Zhang *et al.* (2002) used road density and TM spectral information to form structure-based methods—spectral-structural post-classification comparison and spectral-structural image differencing—to detect urban land change in Beijing, China. Read and Lam (2002) identified that spatial statistics, such as fractal dimension and Moran's *I* index, have the potential to detect land-cover changes. These techniques are not discussed in

this paper in detail because they are specific to a selected research aspect, limited by the data available, or have not yet been used widely.

4. A review of comparative studies of change detection techniques

Section 3 summarized change detection techniques and gave a brief review of their applications. This section will provide a review based on quantitative comparison of accuracy associated with different change detection techniques.

In general, change detection techniques can be grouped into two types: (1) those detecting binary change/non-change information, for example, using image differencing, image ratioing, vegetation index differencing and PCA; and (2) those detecting detailed 'from-to' change, for example, using post-classification comparison, CVA and hybrid change detection methods. One critical step in using the methods for change/non-change detection is to select appropriate threshold values in the tails of the histogram representing change information. A detailed discussion about the determination of a threshold is provided in §6. In detailed 'from-to' change detection, the key is to create accurate thematic classification images. The errors of individual-date thematic images will affect the final change detection accuracy.

In practice, an analyst often selects several methods to implement change detection in a study area, then compare and identify the best results through accuracy assessment. Muchoney and Haack (1994) examined several approaches in detecting defoliation, including merged PCA, image differencing, spectral/temporal change classification, and post-classification comparison. They found classification of principal components and the difference images could yield generally higher classification accuracies than the other methods. The overall accuracy ranged from 61% (post-classification, spectral-temporal) and 63% (PCA) to 69% (image differencing) relative to traditional air survey approaches to monitoring defoliation. Mas (1997, 1999) compared six methods—image differencing, vegetation index differencing, selective PCA, direct multi-temporal unsupervised classification, post-classification change differencing, and a combination of image enhancement and post-classification comparison—at a coastal zone of the state of Campeche, Mexico, and concluded that post-classification comparison was the most accurate procedure and had the advantage of indicating the nature of the change. The overall accuracy for change/non-change level ranged from 73–87%, with post-classification comparison being the best. MacLeod and Congalton (1998) examined post-classification comparison, image differencing and PCA for determining the change in eelgrass meadows using Landsat TM data. The reference data were collected through aerial photography combined with a boat-based survey. A proposed change detection error matrix was used to quantitatively assess the accuracy of each technique. They found that the image differencing technique performed significantly better than post-classification comparison and PCA, with the overall accuracy for the change/non-change error matrix being 78% with a Khat of 0.41. Michener and Houhoulis (1997) evaluated five unsupervised change detection techniques using multi-spectral and multi-temporal SPOT HRV data for identifying vegetation response to extensive flooding of a forested ecosystem associated with tropical storm Alberto. The techniques were spectral-temporal change classification, temporal change classification based on NDVI, PCA of spectral data, PCA of NDVI data, and NDVI image differencing. Standard statistical techniques, logistic multiple regressions and a probability vector model were used to quantitatively and visually assess classification accuracy. It was found that the classification accuracy

was improved when temporal change classification based on NDVI data was used. Both PCA methods were more sensitive to flood-affected vegetation than the temporal change classifications based on spectral and NDVI data. Vegetation changes were most accurately identified by image differencing of NDVI data (overall accuracy was 77%). Yuan and Elvidge (1998) compared image differencing, ratioing, PCA and post-classification comparison associated with different image normalization methods including dark and bright set, pseudo-invariant feature, and automated scattergram controlled regression and concluded that the automated scattergram controlled regression between normalized image differencing and NDVI differencing provided best change/non-change detection results. Dhakal *et al.* (2002) compared image differencing, PCA and CVA for detection of areas associated with flood and erosion using multi-temporal TM data in the central region of Nepal. They found that CVA provided high spatial agreement (88%) in change/non-change categories.

Although a large number of change detection applications have been implemented and different change detection techniques have been tested, conclusion on which method is best suitable for a specific study area remains unanswered. It shows that no single method is suitable for all cases. Which method is selected depends on an analyst's knowledge of the change detection methods and the skill in handling remote sensing data, the image data used, and characteristics of the study area. Because of the difficulty in identifying a suitable method, in practice different change detection techniques are often tested and compared to provide a best result based on the accuracy assessment or qualitative assessment. Previous research has shown that a combination of two change detection techniques, such as image differencing and PCA, NDVI and PCA, or PCA and CVA, could improve the change detection results. The most common change detection methods are image differencing, PCA, CVA and post-classification comparison.

5. Change detection at a global scale

Many researchers use high or moderate spatial resolution remotely sensed data such as TM, SPOT and radar. However, at continental or global scale, such sensors generate huge amounts of data that make it difficult and expensive to implement analysis. Coarse resolution data such as MODIS or AVHRR are often useful and more practicable for many types of change detection. The advantages of daily availability, low cost and low spatial resolution of National Oceanic and Atmospheric Administration (NOAA) AVHRR data have made it the best source of spectral data for large area change detection. For example, the NOAA AVHRR data have been used for monitoring temporal changes associated with vegetation (Turcotte *et al.* 1989, Batista *et al.* 1997), tropical deforestation (Di Maio-Mantovani and Setzer 1996), monitoring and damage evaluation of flood (Liu *et al.* 2002), LULC change (Lambin and Ehrlich 1996, 1997) and forest fire detection (Cuomo *et al.* 2001). In recent years unmixing analysis of coarse resolution satellite images has been used for land-cover change detection (Holben and Shimabukuro 1993, Shimabukuro *et al.* 1994, Mùcher *et al.* 2000) and GIS approach for deforestation detection in Amazon forests (Di Maio-Mantovani and Setzer 1996).

Annual integrated or isolated dates of AVHRR vegetation index data were used to document the inter-annual variations in primary production in the Sahel (Tucker *et al.* 1986, 1991) and to quantify large-scale tropical deforestation (Nelson and Holben 1986, Malingreau *et al.* 1989). Justice *et al.* (1986) used AVHRR data to

detect vegetation change in east Africa. Lambin and Strahler (1994a) combined PCA and CVA to detect land-cover change in west Africa using time trajectories of AVHRR NDVI. The results have proved to be effective in detecting and categorizing inter-annual change between time trajectories of NDVI data. In another article, they compared vegetation indices, land surface temperature and spatial structure to detect and categorize land-cover change and found that the NDVI detects inter-annual variations such as vegetation growth and senescence. They also found that land surface temperature detects the variability at short timescale which responds to short-term variations in energy balance, and that spatial structure detects long-term processes related to structural changes in landscape ecology. They recommended the combination of these three indicators for land-cover change detection (Lambin and Strahler 1994b). Afterwards, Lambin and Ehrlich (1996, 1997) used surface temperature and vegetation index to detect LULC change in Africa.

MODIS data have also shown promising applications in LULC change detection. Zhan *et al.* (2000) implemented the generation procedure to produce land-cover change products using 250 m resolution MODIS data. Five change detection methods were tested: the red–near-infrared (NIR) space partitioning method, red–NIR space change vector, modified delta space thresholding, changes in the coefficient of variation, and changes in linear features. They found that different methods identified different pixels as change, requiring use of multiple methods to gain confidence in the change detection results. The 250 m vegetation cover conversion product and above-mentioned five change detection methods were also used to monitor Idaho–Montana wildfires, the Cerro Grande prescribed fire in New Mexico, flood in Cambodia, Thailand–Laos flood retreat, and deforestation in southern Brazil (Zhan *et al.* 2002). More detailed information about the MODIS instrument characteristics, product quality assessment and validation, analyses and applications can be found in a special issue of *Remote Sensing of Environment* (**83** (1–2), 2002).

A change detection method based on a combination of AVHRR, Landsat TM and SPOT HRV data was evaluated in a study site in Vietnam. High spatial resolution imagery were related to AVHRR-derived forest class proportions and fragmentation patterns to monitor forest area change (Jeanjean and Achard 1997). Borak *et al.* (2000) also examined the ability of several temporal change metrics to detect land-cover change in sub-Saharan Africa through combination of high and coarse spatial resolution data. They found that coarse spatial resolution temporal metrics are most effective as land-cover change indicators when various metrics are combined in multivariate models. Serneels *et al.* (2001) implemented land-cover change detection around an east African wildlife reserve using a combination of time contextual and spatial contextual change detection methods. They found that coarse spatial resolution data (e.g. AVHRR) detected areas that were sensitive to inter-annual climate fluctuation and higher spatial resolution data (e.g. TM) detected land-cover conversions, independent of climate-induced fluctuations.

AVHRR and MODIS data are useful in large area change detection applications. NDVI and land surface temperature derived from thermal bands of AVHRR or MODIS appear to be useful for large area change detection. New change detection techniques are still needed for the analyses of low coarse resolution data. Multi-scale image analysis and multi-source data application will be important in improving large area change detection results. MODIS data associated with different spatial resolutions (250, 500 and 1000 m) and a large

number of multi-spectral bands will become an important scientific bridge between high spatial resolution satellite data such as TM and coarse spatial resolution data such as AVHRR.

6. Selection of thresholds

Many change detection algorithms, such as in algebra and transformation categories, require selection of thresholds to differentiate change from no-change areas (Fung and Ledrew 1988). Two methods are often used for selection of thresholds (Singh 1989, Deer 1995, Yool *et al.* 1997): (1) interactive procedure or manual trial-and-error procedure—an analyst interactively adjusts the thresholds and evaluates the resulting image until satisfied; and (2) statistical measures—selection of a suitable standard deviation from a class mean. The disadvantages of the threshold technique are that: (1) the resulting differences might include external influences caused by atmospheric conditions, Sun angles, soil moistures and phenological differences in addition to true land-cover change; and (2) the threshold is highly subjective and scene-dependent, depending on the familiarity with the study area and the analyst's skill. In order to improve the change detection results, Metternicht (1999) used fuzzy set and fuzzy membership functions to replace the thresholds. Bruzzone and Fernández Prieto (2000a, b) proposed automatic analyses based on the Bayes rule for minimum error and a minimum-cost thresholding technique to determine the threshold that minimizes the overall change detection error probability. An adaptive parcel-based technique was also proposed to reduce the effects of noise produced in the unsupervised change detections (Bruzzone and Fernández Prieto 2000c).

Although some advanced approaches have been developed to improve the change detection results (Metternicht 1999, Bruzzone and Fernández Prieto 2000a, b), these are still less frequently used in practice due to their complexity. However, because of the simplicity and intuitiveness in determination of thresholds, the threshold method is still the most extensively applied in detecting binary change and no-change information even though the disadvantages of selecting suitable thresholds exist.

7. Accuracy assessment

Accuracy assessment is very important for understanding the developed results and employing these results for decision-making. The most common accuracy assessment elements include overall accuracy, producer's accuracy, user's accuracy and Kappa coefficient. Previous literature has provided the meanings and methods of calculation for these elements (Congalton *et al.* 1983, Hudson and Ramm 1987, Congalton 1991, Janssen and van der Wel 1994, Kalkhan *et al.* 1997, Biging *et al.* 1999, Congalton and Green 1999, Smits *et al.* 1999, Congalton and Plourde 2002, Foody 2002). For example, Congalton (1991), Janssen and van der Wel (1994), Smits *et al.* (1999) and Foody (2002) reviewed accuracy assessment for classification of single-date remotely sensed data and discussed some specific issues related to the accuracy assessment. The book *Assessing the Accuracy of Remotely Sensed Data: Principles and Practices* by Congalton and Green (1999) systematically discusses the concepts of basic accuracy assessment besides some advanced topics involved in fuzzy logic and multi-layer assessment and explained principles and practical considerations of designing and conducting accuracy assessment of remote sensing data. In particular, this book discussed sampling design, data collection,

development and analysis of an error matrix and provided a case study for the assessment of accuracy of single-date remote sensing data.

The accuracy assessment for change detection is particularly difficult due to problems in collecting reliable temporal field-based datasets. Therefore, much previous research on change detection cannot provide quantitative analysis of the research results. Although standard accuracy assessment techniques were mainly developed for single-date remotely sensed data, the error matrix-based accuracy assessment method is still valuable for evaluation of change detection results. Some new methods have also been developed to analyse the accuracy of change detection (Morisette and Khorram 2000, Lowell 2001). Morisette and Khorram (2000) used 'accuracy assessment curves' to analyse the satellite-based change detection and Lowell (2001) developed an area-based accuracy assessment method for analysis of change maps. A monograph, 'Accuracy assessment of remote sensing-derived change detection', edited by Siamak Khorram (Biging *et al.* 1999) is specifically focused on accuracy assessment of land-cover change detection. This monograph describes the issues affecting accuracy assessment of land-cover change detection, identifies the factors of a remote sensing processing system that affects accuracy assessment, presents a sampling design to estimate the elements of the error matrix efficiently, illustrates possible applications, and gives recommendations for accuracy assessment of change detection.

The error matrix is the most common method for accuracy assessment. In order to properly generate an error matrix, one must consider the following factors (Congalton and Plourde 2002): (1) ground truth data collection, (2) classification scheme, (3) sampling scheme, (4) spatial autocorrelation, and (5) sample size and sample unit. Other important accuracy assessment elements, such as overall accuracy, omission errors, commission errors and KHAT coefficient can be developed using the error matrix. Sampling design is one of the most important considerations in the collection of ground truth data. Biging *et al.* (1999) recommended a geographically based multi-stage stratified random sample associated with field plots of approximately 3×3 pixels in size when implementing change detection accuracy assessment.

Accuracy assessment is an important part in remote sensing classification and change detection applications. Interested readers should look at Congalton and Green (1999) and Biging *et al.* (1999) which are two books devoted solely to accuracy assessment of remote sensing data.

8. Summary and recommendations

Precise geometrical registration and atmospheric correction or normalization between multi-temporal images are prerequisites for a change detection project. The crucial factors for successfully implementing change detection are selecting suitable image acquisition dates and sensor data, determining the change categories, and using appropriate change detection algorithms. Identifying a suitable change detection technique has considerable significance for a study area to produce good change detection results.

Those change detection techniques based on determination of thresholds for identification of changes from unchanged areas have a common problem: it is difficult to distinguish true changed areas from the detected change areas. For example, in agricultural lands, the change detection based on thresholds is often misleading due to the different phenological characteristics of crops. Change detection based on classification methods can avoid such problems, but requires

considerable effort to implement classification. Recently, LSMA and ANN have shown promise for change detection applications. The LSMA approach has been shown to be an effective method for monitoring Earth's surface changes (Roberts *et al.* 1997). GIS also has proved to be a useful tool in many change detection applications, in particular when multi-source data are used.

Common remotely sensed data used for change detection are MSS, TM, SPOT, AVHRR, radar and aerial photographs. The types of remote sensing data selected depend on the objectives and requirements of a specific project and the data available in the study area. For a local area, middle-level resolution data such as TM, SPOT and radar are often used, but for a large study area (e.g. regional or global), coarse resolution data such as MODIS and AVHRR are most suitable. High spatial resolution satellite sensors can provide reliable land cover classification and change detection results at a local level. However, for a large area, high resolution satellite data offer a huge amount of data, presenting a great challenge to analyse them due to the processing loads, time and cost. Coarse spatial resolution satellite sensors have advantages of frequent coverage of large areas and their data facilitate classification and change detection of land cover in a large area, but it is difficult to attain results similar to those derived from high resolution sensor data.

The application of multi-sensor data provides the potential to more accurately detect land-cover changes through integration of different features of sensor data. The disadvantage of using multi-sensor data for change detection is the difficulty in image processing and selection of appropriate change detection techniques. In practice, acquiring the same sensor data in multi-temporal format is sometimes difficult, especially in moist tropical regions due to effects of clouds. For a change detection application covering a long time period, data from different sensors have to be used because single-sensor data may not be available. For example, MSS data are available after 1972, TM data after 1983, SPOT data after 1986 and ETM+ data after 1999. Application of multi-sensor data will become increasingly important in future change detection research, and thus more advanced change detection techniques are needed.

Change detection analysis remains an active research topic and new techniques continue to be developed. For a new change detection technique, it is important to be able to implement it easily and for it to provide accurate change detection results associated with change trajectories. Although a variety of change detection techniques have been developed, it is still difficult to select a suitable method to implement accurate change detection for a specific research purpose or study area. Selection of a suitable change detection method requires careful consideration of major impact factors. In practice, several change detection techniques are often used to implement change detection, whose results are then compared to identify the best product through visual assessment or quantitative accurate assessment.

Despite many factors affecting the selection of suitable change detection methods, image differencing, PCA and post-classification are, in practice, the most commonly used. In recent years, LSMA, ANN and GIS have become important techniques to improve change detection accuracy. The following are some specific recommendations.

- (1) For a rapid qualitative change detection analysis, visual interpretation of multi-temporal image colour composite is still a common and valuable method.

- (2) For digital change detection of change/non-change information, single-band image differencing and PCA are the recommended methods.
- (3) For a detailed 'from-to' detection, post-classification comparison is a suitable method to implement when sufficient training sample data are available.
- (4) When multi-source data are used for change detection, GIS techniques are helpful.
- (5) Advanced techniques such as LSMA, ANN or a combination of different change detection methods can be useful to produce higher quality change detection results.

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