

Methods for fuzzy classification and accuracy assessment of historical aerial photographs for vegetation change analyses. Part I: Algorithm development

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Image classification of historical aerial photographs is very useful for the study of medium-to-long term (10–50 years) vegetation changes. To determine the quality of information derived from the classification process, accuracy assessment of the classification is implemented. Error matrix, which is primarily used in remote sensing for accuracy assessment, is typically based on an evaluation of the derived classification against some ‘ground truth’ or reference dataset. Regrettably ‘ground truths’ for some old historical photographs are rarely available. To solve this problem we formulate, in this Part I, methods of classification of aerial photographs and computation of accuracy assessment parameters of classification products in the absence of ground data, using the fuzzy classification technique. In addition, since point estimates of these accuracy parameters require associated standard errors, in order to be useful for statistical analysis, the method of computation of standard errors of accuracy measures using the bootstrap resampling techniques is presented. These methods are tested with historical aerial photographs, of part of Adulam Nature Reserve, Israel, spanning a period of 51 years. Results illustrate the applicability and efficiency of the proposed methods.

1. Introduction

Historical aerial photographs have much longer temporal history than satellite-derived data, and offer the potential for more detailed landscape ecological assessments. They provide a much longer time frame for assessing the magnitude of change and for predicting change based on long-term trends (Lo 1986). Aerial photographs have been available for, at least, the past five decades for most part of the world. In addition, aerial photographs have high spatial resolution and therefore offer the possibility of providing more detailed local and regional vegetation information. Most importantly, the advances in digital photogrammetry, digital image processing, and geographic information systems (GIS) have further increased the potential for the use of historical aerial photographs for vegetation change analyses. Thus, there has been an increased use of historical aerial photographs for change analyses. Carmel and Kadmon (1998), Kadmon and Harari-kremer (1999) compared manual interpretation and digital image processing of panchromatic aerial photographs. They found the accuracy to be similar, and stated the advantages of digital processing over manual processing of aerial photographs for

change analysis. Others studies include Hudak and Wessman (1998), Turner *et al.* (1996), Turner (1990), Coppedge *et al.* (2001) and Aaviksoo (1993).

Image classification is performed in order to derive specific information, on the amount and spatial distribution of various types of land use and land cover, from remotely sensed data (i.e. satellite imagery, aerial photographs), and is generally regarded as the process of creating thematic maps from images (Campbell 1996, Lillesand and Kiefer 2000). Most traditional classification methods are 'crisp' or 'hard' partitioning, in which every given object is strictly classified into a certain group. In practice, mixed pixels occur because the pixel size may not be fine enough to capture detail on the ground necessary for specific applications or where the ground properties, such as vegetation and soil types, vary continuously, as almost everywhere. The result of hard classification is one class per pixel, whereby much information about the memberships of the pixel to other classes is lost. Allowing pixels to have multiple and partial class membership, in which pure and mixed pixels are accommodated in the classification process, has generally been the solution of the mixed pixel problem. This is achieved, among other methods, by soft classification technique, which assigns a pixel to several land cover classes in proportion to the area of the pixel that each class covers. Fuzzy c-means algorithm has been shown in various literatures to be one of the most popular soft classification techniques (Wu and Yang 2002, Yang *et al.* 2003).

In order to use the products of classification efficiently, users need to know how accurate these products are. Classification accuracy assessment is therefore an important stage in the image classification process. One of the most common ways of representing accuracy assessment information is in the form of an error matrix, or contingency table. Construction of an error matrix requires the availability of reference data or ground truth. Unfortunately, for some practical cases of the classification of historical aerial photographs, the ground data are not available. For cases where crisp outputs are required, fuzzy classification partitions can be used to construct a fuzzy error matrix in the absence of ground data.

This paper addresses the problem of lack of ground data in the classification and accuracy assessment of aerial photographs for change analysis, and describes methods of solution using the fuzzy classification technique. Section 2 of this paper describes fuzzy c-means algorithms, which is one of the most popular soft classification techniques. Section 3 presents the technique of accuracy assessment of classification products in the absence of ground data, including the application of the bootstrap resampling method. Techniques presented in this work are tested using real datasets described in §4, with programs developed in Matlab version 6.5, and results are presented in §5. Discussions and conclusions are presented in §6 and §7, respectively.

2. Fuzzy c-means (FCM) algorithms

The soft classification technique, which assigns a pixel to several land cover classes in proportion to the area of the pixel that each class covers, is one of the methods of solution of the mixed pixel problem. In the literature on soft classifications the fuzzy c-mean (FCM) algorithms are the most popular methods (Bastin 1997, Wu and Yang 2002, Yang *et al.* 2003).

Like in the hard techniques the unsupervised fuzzy classification method (also known as fuzzy clustering) does not require an extensive prior knowledge of the area and unique classes are recognized as distinct units. Foody (2000) showed that supervised FCM may be used to derive accurate estimates of sub-pixel land cover

composition especially when all classes have been defined and included in the training stage of the classification and that the presence of an untrained class degrades the accuracy of sub-pixel class composition estimation.

Fuzzy c-mean (FCM) is an unsupervised classification or clustering algorithm that has been applied successfully to a number of problems involving feature analysis, clustering and classifier design, such as in agricultural engineering, remote sensing, astronomy, chemistry, geology, image analysis, medical diagnosis and shape analysis. It is a clustering algorithm that has commonly been adapted for supervised classification of remotely sensed imagery (Foody 1996, Atkinson *et al.* 1997, Deer 1998, Deer and Eklund 2003). The modification from unsupervised to supervised classification involves the specification of fuzzy means and sometimes also fuzzy covariance matrices, and requires only a single pass of the data through the algorithm (Deer 1998, Foody 2000, Deer and Eklund 2003).

The FCM algorithm is based on an iterative optimization of an objective function J_m , which is the weighted sum of squared errors within groups and is defined as follows (Bezdek 1981):

$$J_m(U, V; X) = \sum_{k=1}^n \sum_{i=1}^c U_{ik}^m \|x_k - v_i\|_A^2, \quad 1 < m < \infty, \quad (1)$$

where U is a fuzzy c-partition of X . $X = \{x_1, x_2, \dots, x_n\}$ is a finite dataset in the pattern space \mathbf{R}^s , c is a fixed and known number of cluster, $V = (v_1, v_2, \dots, v_c) \in \mathbf{R}^{cs}$ with $v_i \in \mathbf{R}^s \forall i$ being the cluster prototype or cluster centre of class i , $1 \leq i \leq c$. The parameter m is the weighting exponent for each fuzzy membership, which determines the ‘degree of fuzziness’, $1 \leq m < \infty$. If $m=1$, then the algorithm reduces to the hard c-means algorithm. $U = [u_{ik}] \in \mathbf{R}^{cn}$ is referred to as the grade of membership of x_k to the cluster i . u_{ik} satisfies the following constraints:

$$\begin{aligned} u_{ik} &\in [0, 1]; \quad 1 \leq i \leq c, \quad 1 \leq k \leq n; \\ \sum_{i=1}^c u_{ik} &= 1; \quad 1 \leq k \leq n; \\ 0 < \sum_{k=1}^n u_{ik} &< n; \quad 1 \leq i \leq c; \end{aligned} \quad (2)$$

$\|x_k - v_i\|_A^2$ is an inner product induced norm on \mathbf{R}^s ; A is any (sxs) symmetric positive definitive matrix. Bezdek (1981) showed that for $\|x_k - v_i\|_A > 0, \forall i, \forall k$, then J_m is minimized only when $m > 1$, and

$$v_i = \frac{\sum_{k=1}^n (u_{ik})^m x_k}{\sum_{k=1}^n (u_{ik})^m}, \quad 1 \leq i \leq c, \quad (3)$$

$$u_{ik} = \frac{1}{\sum_{j=1}^c \left(\frac{\|x_k - v_i\|_A^2}{\|x_k - v_j\|_A^2} \right)^{1/m}}, \quad 1 \leq i \leq c, \quad 1 \leq k \leq n. \quad (4)$$

There are many extensions of the original FCM algorithm. Prominent amongst them are the Gustaffson-Kessel (GK) algorithm (Gustafson and Kessel 1979), and Gath-Geva (GG) algorithm (Gath and Geva 1989). In this paper, we use the GK model for the fuzzy classification process.

In general, FCM algorithms depend on certain assumptions in order to define the subgroups present in a dataset. These assumptions include the optimal number of classes, c , the initial centroid values, the initial partition, U^0 , the optimal fuzzy exponent, m value, and the iteration termination threshold, ε value. The optimal number of classes, c , may be known *a priori* or determined by cluster validity process. Detailed studies of the performance of different validity indices can be found in Pal and Bezdek (1995, 1997), and Geva *et al.* (2000). However, in this paper, we determine optimal number of clusters by first partitioning the dataset into an exaggerated number of clusters. Then by visually verifying different clusters in Erdas Imagine software, we determine clusters to merge in order to form an optimal number of clusters.

The fuzzy exponent m must also be chosen in order to implement the FCM algorithm, and its determination is problematic (Pal and Bezdek 1995, 1997). Many past works have proposed methods of determining optimal fuzzy exponent m . These include the procedures proposed in McBratney and Moore (1985) and Choe and Jordan (1992). However, many researchers simply use $m=2$ as the ideal fuzzy exponent. In this paper, we use a new and efficient procedure to determine an optimal fuzzy exponent. In this procedure, the output of the fuzzy classification is used to predict the original dataset. Then the fuzzy exponent value that corresponds to the least distance between the predicted data and the original dataset, for a range of fuzzy exponent values, becomes the optimal value. This is illustrated by equation (5) below.

$$\|X - \hat{X}^*\| = \sigma, \sigma > 0, \forall m \quad (5)$$

where X is the original dataset, \hat{X}^* is the predicted dataset, and $\|\cdot\|$ is any suitable similarity measure or distance metric, such as Euclidean distance, divergence distance, Bhattacharyya distance or angular separation. The predicted dataset is obtained by pre-multiplying the membership grades matrix by the class centroid matrix.

3. Accuracy assessment of the classification of historical aerial photographs

There is no classification created from remote sensing data that can be completely accurate as errors originate from different sources including the classification algorithm itself (Steele *et al.* 1998, Smits *et al.* 1999). In order to use the products of classification efficiently, the user needs to know how accurate these products are. This therefore necessitated accuracy assessment of the remote sensing classification process. In remote sensing, accuracy assessment is mandatory (Matsakis *et al.* 2000, Foody 2002), and is important for providing information about the quality of the product of classification as well as furnishing the norms for comparing the performance of different classification methods.

One of the most common ways of representing accuracy assessment information is in the form of an error matrix, or contingency table (Congalton 1988, 1991, 1993, Congalton and Green 1998, Binaghi *et al.* 1999, Nishii and Tanaka 1999, Smits *et al.* 1999, Lewis and Brown 2001, Foody 2002). Error matrix provides a detailed

assessment of the agreement between the sample reference data and classification data at specific locations, together with a complete description of the misclassifications registered for each category. In addition to the valuable role of the error matrix, a number of descriptive and analytical statistical techniques, based on the error matrix, have been proposed. These are used for summarizing information and for obtaining accuracy measures that can meet specific objectives. The most commonly used are the overall accuracy, user's and producer's accuracy, and various forms of kappa coefficients of agreement. Using an error matrix to represent accuracy has been recommended by many researchers and is central to accuracy assessment in remote sensing (Binaghi *et al.* 1999, Nishii and Tanaka 1999, Smits *et al.* 1999, Lewis and Brown 2001, Foody 2002).

However, the error matrix and the derived accuracy measures are appropriate only for hard classification with the assumption that each element of sample data is associated with only one class in the classification and only one class in the reference data (Gopal and Woodcock 1994, Foody 1995, Foody and Trodd 1996, Binaghi *et al.* 1999, Matsakis *et al.* 2000, Woodcock and Gopal 2000). For evaluation of soft classification, various investigations have been made and many suggestions put forward, some of which are presented in Gopal and Woodcock (1994), Foody (1995), Foody and Trodd (1996), Binaghi *et al.* (1999), Ahlqvist *et al.* (2000), Jaeger and Benz (2000), Woodcock and Gopal (2000). The procedures of 'fuzzy error matrix' of Binaghi *et al.* (1999), 'fuzzy similarity' of Jaeger and Benz (2000), and the method of Ahlqvist *et al.* (2000) are based on fuzzy logic and also retain the attractive features and popularity of the confusion matrix. Again, these measures can be applied when either classification or ground data is crisp, and if both are crisp, they often reduce to standard measures already in use. In this paper, we apply the method of 'fuzzy error matrix' of Binaghi *et al.* (1999) for the accuracy assessment of classification of aerial photographs.

3.1 Building fuzzy error matrix in the absence of ground data

The fuzzy error matrix of Binaghi *et al.* (1999) is constructed as follows: Let \tilde{R}_n be the set of fuzzy reference data assigned to class n , and \tilde{C}_m be a set of fuzzy classification data assigned to class m , with $1 \leq n \leq Q$, $1 \leq m \leq Q$, and Q as the number of classes. The fuzzy partitions \tilde{R}_n and \tilde{C}_m are partitions of the dataset X , and their membership functions are

$$u_{\tilde{R}_n}: X \rightarrow [0, 1], \tag{6}$$

$$u_{\tilde{C}_m}: X \rightarrow [0, 1], \tag{7}$$

where $[0,1]$ denotes the interval of real numbers from 0 to 1 inclusive. The fuzzy error matrix is then given as

$$\tilde{M}(m, n) = |\tilde{C}_m \cap \tilde{R}_n| = \sum_{x \in X} u_{\tilde{C}_m \cap \tilde{R}_n}(x). \tag{8}$$

Where the 'min' operator is introduced for the intersection operation as $u_{\tilde{C}_m \cap \tilde{R}_n}(x) = \min(u_{\tilde{C}_m}(x), u_{\tilde{R}_n}(x))$. As in the conventional error matrix, the fuzzy error matrix can be used to compute descriptive statistics such as the overall accuracy, producer's accuracy, user's accuracy, and kappa coefficient.

The construction of the error matrix requires a reference data or ground truth. In most of the literature, it is assumed that the ground or reference data used in the

assessment of classification accuracy are themselves accurate representations of reality (Foody 2002). Actually, the ground data are just another classification which may contain error (Congalton and Green 1998, Zhou *et al.* 1998, Lunetta *et al.* 2001, Foody 2002). Again the certainty with which a label can be attached to a class is often based on highly subjective interpretations (Thierry and Lowell 2001, Foody 2002). Therefore, it may be inappropriate to use the term 'truth' when describing ground data (Bird *et al.* 2000, Foody 2002). Thus, the accuracy assessment referred to in the foregoing may best be described as measuring the degree of agreement or correspondence to the ground data and are not necessarily a true reflection of the closeness to reality (Foody 2002).

Reference data are usually collected from data sources that are assumed to be more accurate and precise than the data to be classified. Aerial photography is often used as reference source data for accuracy assessment of classification of satellite imagery (Congalton and Green 1998). For the classification of aerial photographs themselves, a ground survey may be the only reliable method of reference data collection. Unfortunately, in some practical cases, the ground survey cannot be undertaken since the aerial photographs were collected many years before the study. Example of such cases are studies where historical aerial photographs, dating back to many decades, are used for vegetation change analysis and/or studies of certain temporal ecological processes, and where classification algorithms are used for labelling different classes of the domain of interest. A ground survey for such cases cannot be carried out as a long time has elapsed since the data was collected. In cases where it is not possible to provide ground data, such as in the classification of historical aerial photographs, researchers often resort to different ad hoc approaches, which place heavy reliance on the capability of the analyst to interpret and identify classes of the domain. For instance, in Carmel and Kadmon (1998), training data for a photograph, where ground data was not available, was generated by measuring the height of individual shrubs and trees, based on a stereo image of the photograph.

For cases where crisp outputs are required, fuzzy classification partitions can be used to solve this problem by providing a means to assess the accuracy of the crisp products. This idea was first illustrated in Wang (1990a, b). The idea of using fuzzy partition to assess the accuracy of crisp classification output is based on the assumption and assertion that membership grade of fuzzy partition is proportional to the percentage to which the pixel contains a given type of land cover (Wang 1990a, b). Thus, the fuzzy partition matrix is regarded as more accurate and precise than its hard counterpart. Other studies have all suggested, with varying degrees of empirical support, that there is a strong relationship between fuzzy memberships and true proportions of ground cover. These include Fisher and Pathirana (1990), Foody (1992a, 1994, 1996), Foody and Cox (1994), Maselli *et al.* (1996), Atkinson *et al.* (1997), Canters (1997), Deer (1998), and Deer and Eklund (2003). However, Schowengerdt (1996) cautioned against the use of likelihood indicators (fuzzy memberships derived partly using hard statistical pattern classification approaches) as a global measure of class mixing proportions, especially for classes having relatively low separability and considerable distribution overlap. Also Deer and Eklund (2003) pointed out some cases where fuzzy memberships did not equal class proportion. Excluding these special cases, it is generally accepted and assumed that fuzzy partitions have strong correlation with true class mixing proportions. Based on this assumption, we present in

this paper a method of constructing the fuzzy error matrix in the absence of ground data.

Let us consider a situation where the crisp product of the classification procedure is desired. After the fuzzy classification of the dataset is performed, the fuzzy partition is transformed to a crisp partition by the process of defuzzification. Generally, in remote sensing, the defuzzification process is performed by assigning the elements of the fuzzy partition to the class to which they have the highest probability or the highest possibility of belonging (Matsakis *et al.* 2000). Let $\tilde{U} = (\tilde{u}_i), i \in 1 \dots c$ be a fuzzy partition of dataset X , then the crisp partition $\tilde{V} = (\tilde{v}_i), i \in 1 \dots c$ of the dataset X is the result of defuzzification of \tilde{U} such that:

$$\tilde{v}_{jk} = \begin{cases} 1 \Rightarrow \tilde{u}_{jk} = \max\{\tilde{u}_{ji} | 1 \leq i \leq c\}, \\ 0 \Rightarrow \tilde{u}_{jk} \neq \max\{\tilde{u}_{ji} | 1 \leq i \leq c\}. \end{cases} \tag{9}$$

Using equation (8) the fuzzy error matrix is constructed by taking the crisp partition \tilde{V} as the classification partition and the fuzzy partition \tilde{U} as the reference partition.

$$\tilde{M} = |\tilde{V} \cap \tilde{U}| = \sum_{x \in X} u_{\tilde{v} \cap \tilde{u}}(x). \tag{10}$$

Once the fuzzy error matrix is constructed, other descriptive and analytical statistics are computed as in the case of the traditional error matrix.

3.2 Estimates of variances and confidence intervals for measures of classification accuracy

Table 1 is an example of an error matrix that effectively summarizes the key information obtained from comparing the classification and reference data. The error matrix represents a table in which the diagonal entries represent correct classifications, or agreement between the classification and reference data, and the off-diagonal entries represent misclassifications, or lack of agreement between the classification and reference data. In remote sensing, a variety of measures have been suggested for describing the accuracy of classification from the error matrix (Congalton 1991, Stehman 1997a, b, Congalton and Green 1998, Stehman and Czaplewski 1998). These include the overall proportion of area, pixel or polygon classified correctly for the entire area, various forms of kappa (k) coefficient of agreement, conditional kappa, user's and producer's accuracy. In table 1, p_{ij} is the proportion of area in classified land-cover class i and reference land-cover class j , $p_{i+} = \sum_{j=1}^c p_{ij}$ is the proportion of area classified into land cover class i , and $p_{+j} = \sum_{i=1}^c p_{ij}$ is the reference proportion of area in land cover class j .

Table 1. Example of error matrix for a land cover scheme of c classes.

Reference					
Classification	1 2 ... c				
	1	p_{11}	p_{12}	\dots	p_{1c}
2	p_{21}	p_{22}	\dots	p_{2c}	p_{2+}
\vdots	\vdots	\vdots	\vdots	\vdots	\vdots
c	p_{c1}	p_{c2}	\dots	p_{cc}	p_{c+}
	p_{+1}	p_{+2}	\dots	p_{+c}	

Definitions of some of these accuracy measures based on the developments in Congalton (1991, 1993), Stehman (1997a, b), Congalton and Green (1998), Stehman and Czaplewski (1998) follow.

1. Overall proportion of area correctly classified,

$$P_o = \sum_{k=1}^c P_{kk}. \quad (11)$$

2. Kappa,

$$k = \frac{P_o - \sum_{k=1}^c P_{k+} P_{+k}}{1 - \sum_{k=1}^c P_{k+} P_{+k}}. \quad (12)$$

3. Kappa with random chance agreement,

$$k_e = \frac{P_o - 1/c}{1 - 1/c}. \quad (13)$$

4. User's accuracy for class i,

$$P_{Ui} = \frac{P_{ii}}{P_{i+}}. \quad (14)$$

5. Producer's accuracy for cover type j,

$$P_{Aj} = \frac{P_{jj}}{P_{+j}}. \quad (15)$$

6. The conditional Kappa for the map classification category (row) i,

$$k_i = \frac{P_{ii} - P_{i+} P_{+i}}{P_{i+} - P_{i+} P_{+i}} = \frac{P_{Ui} - P_{+i}}{1 - P_{+i}}. \quad (16)$$

7. Conditional Kappa for the reference classification in category (column) j,

$$k_j = \frac{P_{Aj} - P_{j+}}{1 - P_{j+}}. \quad (17)$$

Though no consensus has been reached on which measures are appropriate for a given objective of accuracy assessment, the kappa statistic is most often applied in remote sensing (Stehman 1997b, Congalton and Green 1998, Foody 2002). Stehman (1997b) showed in detail that no one accuracy measure is universally best for all accuracy assessment objectives, and proposes criteria for selecting appropriate accuracy measures for specific study. Congalton and Green (1998) recommended computation of several accuracy measures since each accuracy measure reflects different information contained within the error matrix. Also, since total enumeration of the classified area for verification is at most times impossible, accuracy assessment of classification of remote sensing data usually requires sampling of reference data and estimation of parameters describing classification accuracy. As these accuracy estimates are based on samples, point estimates of these accuracy parameters clearly require associated standard errors, confidence intervals, and significant tests in order to be useful for statistical analysis. There are certain

techniques for estimating standard errors and constructing confidence intervals for measures of classification accuracy derived from the error matrix. One method is to derive formulas for standard errors of these accuracy measures, based for example, on large sample methods or a finite population sampling technique, and using the standard errors estimated to construct confidence intervals based on a normal distribution assumption (Czaplewski 1994, Stehman 1997a, b, Stehman and Czaplewski 1998, Blackman and Koval 2000).

The use of derived formulas for standard errors of the accuracy measures, however, has certain disadvantages. For instance, the formulas derived from the large sample method can become unreliable as sample size decreases or as kappa approaches unity (Vierkant 1997). Again the formulas are design-specific and sometimes may be too complex and difficult to implement. An alternative method of estimating standard errors of accuracy measures derived from the error matrix is the application of resampling techniques such as the bootstrap method of Efron and Tibshirani (1993). This method provides an alternative to large sample techniques when asymptotic properties are not met or when the standard error of the estimate has complicated mathematical characteristics (Vierkant 1997). The bootstrap estimate of standard error requires no theoretical calculations, and is available no matter how mathematically complicated the estimator may be (Efron and Tibshirani 1993). The bootstrap method has been proposed as a suitable alternative for constructing confidence intervals about a kappa coefficient in Kalkhan *et al.* (1997) and Vierkant (1997).

In this paper, we apply the bootstrap resampling method for the estimation of standard errors of classification accuracy measures, and the algorithm we use is described below.

3.2.1 Algorithm for bootstrap estimation of standard errors for classification accuracy parameters

1. Given a dataset, $X=(X_1, \dots, X_n)$, perform classification, generate reference data and classified data (original reference data and original classified data), construct error matrix, and compute parameters of interest, . Where p is the number of parameters of interest.
2. Sample with replacement from the reference data and its corresponding classified data. The number of sample reference data and sample classified data must be the same as the number of original reference data and original classified data.
3. Calculate the same parameters of interest using the sample in step 2 to get the bootstrap replicates, $\hat{\theta}_i^{*b}$, $i = 1, \dots, p$.
4. Repeat steps 2 through 3, B times. Efron and Tibshirani (1993) recommended a B value of 25 to 200.
5. Estimate the standard error of $\hat{\theta}_i$ for each parameter as follows.

$$\widehat{SE}_B(\hat{\theta}_i) = \left\{ \frac{1}{B-1} \sum_{b=1}^B (\hat{\theta}_i^{*b} - \overline{\hat{\theta}_i^{*b}})^2 \right\}^{\frac{1}{2}}, \quad (18)$$

where

$$\overline{\hat{\theta}_i^{*b}} = \frac{1}{B} \sum_{b=1}^B \hat{\theta}_i^{*b}, \forall i. \quad (19)$$

After the bootstrap standard errors of the parameters of interest have been computed, confidence intervals can then be constructed based on normal distribution assumptions (Martinez and Martinez 2002). Confidence intervals are, however, not constructed in this paper since we used the whole population as the sample size.

For change detection studies, the computed standard errors of the kappa coefficients can be used to construct a hypothesis to test for significant differences between error matrices.

Banko (1998) and Skidmore (1999) describe the test of significance between two independent kappa's by the equation

$$Z = \frac{\hat{k}_1 + \hat{k}_2}{\sqrt{\hat{\sigma}(\hat{k}_1) + \hat{\sigma}(\hat{k}_2)}}, \quad (20)$$

where \hat{k}_1 and \hat{k}_2 are kappa coefficients for error matrices 1 and 2 respectively, $\hat{\sigma}(\hat{k}_1)$, $\hat{\sigma}(\hat{k}_2)$ are standard errors of error matrices 1 and 2 respectively. A null hypothesis can be set up to test whether the kappa values for the two error matrices differ significantly.

$$H_0 : k_1 = k_2 \quad \text{versus} \quad H_0 : k_1 \neq k_2.$$

The test for the null hypothesis is performed using the normal curve deviate statistic (z) and appropriate significance level. This procedure can be applied to paired combination of error matrices, to determine whether the error matrices differ significantly (Skidmore 1999).

4. Datasets and methods

4.1 Datasets

Datasets used in testing our proposed methods comprise seven sets of panchromatic aerial photographs of a section of Adulam Nature Reserve, Israel. The datasets spanned a period of 51 years, from 1945 to 1996. The aim is to determine quantitative changes in trees and other vegetation types from 1945 to 1996. There are no ground data available for these photographs. The photographs are for the years 1945, 1956, 1967, 1980, 1984 and 1996. All the photographs were scanned with an A3 UMAX Mirage Iise flatbed scanner at a resolution of 400dpi, into uncompressed, grey scale tiff format images. For georectification, the digital image of 1984 was orthorectified using Erdas Imagine software, orthobase module to the New Israel Grid. Ground control points were provided by a GPS measurement of selected targets on the image. Using the orthorectified image of 1984 as a reference image, the remaining set of 1945, 1956, 1965, 1967, 1980, and 1996 were co-registered to the 1984 orthorectified image. A common subset of area of interest was extracted for each of the georeferenced data. Since the datasets have different scales and image sizes, the whole set was further reshaped and resized to a 1 metre resolution and common image size using programs scripted in Matlab version 6.5. All the other images were radiometrically normalized to the image of 1945 using the histogram-matching procedure of Erdas Imagine software. This is aimed at providing consistent digital number (DN) values for all the dataset.

4.2 Methods

Photo interpretation of the seven datasets revealed three distinct classes that can easily be identified. These are classes of trees, shrubs and herbaceous plants, and bare soil. The three classes intermix so much that it was not possible to further distinguish different classes of trees or shrubs. Fuzzy classification and accuracy assessment of the seven datasets, in the absence of ground data, are performed by applying the following steps:

1. The base dataset (1945 dataset) was classified into 10 classes using the fuzzy algorithm to yield 10 class centroids and a partition matrix. A defuzzification process is performed to identify pixels that show the highest degree of belonging to each of the 10 classes. This is equivalent to the traditional hard classification of the dataset into 10 classes.
2. The hard product is used in Erdas Imagine software environment to visually identify the classes that most likely belong to the class of trees, shrubs and herbaceous plants, and bare soil.
3. Using the result of step 2, appropriate classes of the 10 classes are then merged to form the three major classes of trees, shrubs and herbaceous plants, and bare soil. The merging procedure was performed by merging class centroids of appropriate classes and then re-computing the membership grades in a single pass of the fuzzy algorithm.
4. Using the membership grades obtained in step 3, defuzzification is again performed to obtain pixels most likely to belong to the three classes of trees, shrubs and herbaceous plants, and bare soil. Thus we now have a hard product as well as a fuzzy product of the three classes.
5. Following the procedure described in §3, we take the hard product as the classification data, and the fuzzy membership grades as the reference data, and then compute the fuzzy error matrix using equation(10). Using the computed fuzzy error matrix, accuracy assessment parameters of equation(11) to equation(17) are computed. Subsequently, the bootstrap resampling algorithm described in §3 is used to estimate standard errors of the accuracy assessment parameters, and subsequently other statistical analysis are performed.
6. The class centroids of the classification of 1945 dataset, obtained in step 3, are used in a supervised fuzzy classification mode to compute fuzzy membership grades for each of the rest of the datasets (1956, 1965, 1967, 1980, 1984, and 1996).
7. Steps 4 through 5 are followed for the accuracy assessment of each of the rest of the datasets.

5. Results

Figure 1 shows hard products of fuzzy classification of the seven datasets. The figure shows visually, the distribution of trees, shrubs and herbaceous plants, and bare soil within the area of interest.

Figure 2 shows the percentage coverage of trees, shrubs and herbaceous plants, and bare soil, for the seven datasets. The figure shows a gradual increase in the percentage coverage of trees from 1945 till 1996, with a peak period in 1980. The

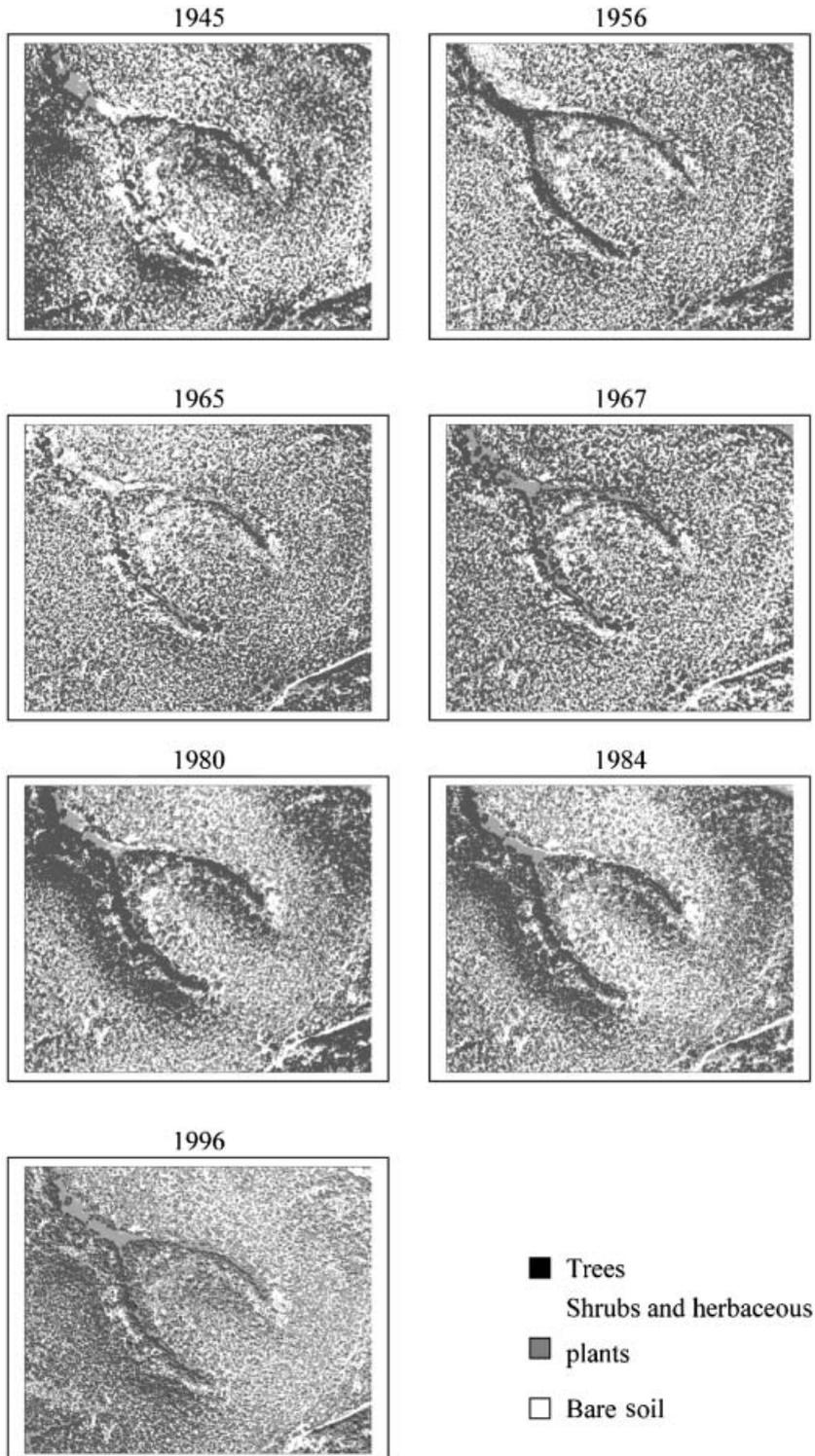


Figure 1. Hard products of the fuzzy classification of the seven datasets.

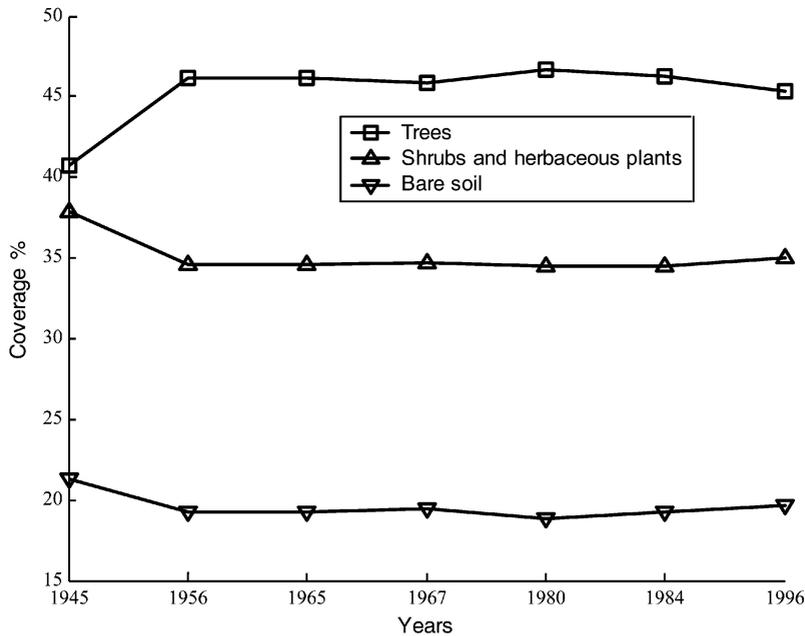


Figure 2. Percentage coverage of the three classes for the seven datasets.

percentage coverage of shrubs and herbaceous plants remained fairly constant between the period 1956 to 1996. A decrease in the percentage coverage of shrubs and herbaceous plants was observed between 1945 and 1956. Also, the percentage coverage of bare soil remained constant from 1956 to 1996 with a slight decrease between 1945 and 1956.

Results of accuracy assessment of the fuzzy classification of the whole datasets are illustrated in tables 2 to 9 and figures 3 to 12. Tables 2 to 8 show the fuzzy error matrix for the datasets 1945, 1956, 1965, 1967, 1980, 1984, and 1996 respectively. Close observation of the computed error matrices show considerable off-diagonal elements between trees and shrubs on one hand, and shrubs and bare soil on the other hand, for all the datasets. These represent a considerable degree of misclassification if hard products are taken as the final classification output.

Figure 3 shows the overall accuracy, kappa coefficient (K), and modified kappa coefficient (K_c) for the whole dataset. All the datasets have higher overall accuracy values than kappa coefficient values. Overall accuracies for all datasets exceeded

Table 2. Fuzzy error matrix for 1945 dataset.

		Reference			Row total
		Tree	Shrubs and herbs	Bare soil	
Classification	Tree	44419.0	3831.5	224.5	48475.0
	Shrubs and Herbs	2958.6	38457.0	1771.7	43187.0
	Bare soil	121.3	1897.0	22880.0	24898.0
	Column total	47499.0	44185.0	24876.0	

Table 3. Fuzzy error matrix for 1956 dataset.

		Reference			Row total
		Tree	Shrubs and herbs	Bare soil	
Classification	Tree	49699.0	3605.3	369.8	53674.0
	Shrubs and herbs	3953.3	35323.0	2561.6	41838.0
	Bare soil	135.7	1405.6	19507.0	21048.0
	Column total	53788.0	40334.0	22438.0	

Table 4. Fuzzy error matrix for 1965 dataset.

		Reference			Row total
		Tree	Shrubs and herbs	Bare soil	
Classification	Tree	49866.0	3750.5	379.2	53996.0
	Shrubs and herbs	3782.8	35271.0	2671.5	41725.0
	Bare soil	126.8	1287.7	19424.0	20839.0
	Column total	53776.0	40309.0	22475.0	

Table 5. Fuzzy error matrix for 1967 dataset.

		Reference			Row total
		Tree	Shrubs and herbs	Bare soil	
Classification	Tree	49891.0	3865.8	382.8	54140.0
	Shrubs and herbs	3371.0	34634.0	2014.7	40020.0
	Bare soil	175.1	1987.6	20237.0	22400.0
	Column total	53438.0	40488.0	22635.0	

85%, while kappa coefficients for all datasets exceeded 80%. Figure 4 shows the bootstrap standard deviation of the overall accuracy, kappa coefficient (K), and modified kappa coefficient (K_e) for the whole dataset. Both kappa coefficients show higher standard deviations than the overall accuracy.

A null hypothesis was constructed to test whether the error matrices differ significantly from one another. The result revealed no significant difference between all paired combinations of the dataset at 0.01, 0.05, and 0.1 significant levels. The

Table 6. Fuzzy error matrix for 1980 dataset.

		Reference			Row total
		Tree	Shrubs and herbs	Bare soil	
Classification	Tree	50400.0	3501.6	370.2	54272.0
	Shrubs and herbs	3875.6	35325.0	2485.1	41686.0
	Bare soil	129.9	1360.1	19112.0	20602.0
	Column total	54406.0	40187.0	21967.0	

Table 7. Fuzzy error matrix for 1984 dataset.

		Reference			Row total
		Tree	Shrubs and herbs	Bare soil	
Classification	Tree	50257.0	4369.5	419.2	55046.0
	Shrubs and herbs	3559.5	34616.0	2807.4	40983.0
	Bare soil	115.7	1166.6	19249.0	20531.0
	Column total	53933.0	40152.0	22475.0	

Table 8. Fuzzy error matrix for 1996 dataset.

		Reference			Row total
		Tree	Shrubs and herbs	Bare soil	
Classification	Tree	50111.0	4840.7	439.1	55391.0
	Shrubs and herbs	2575.2	34666.0	2621.7	39863.0
	Bare soil	131.5	1307.8	19867.0	21306.0
	Column total	52818.0	40815.0	22928.0	

computed z statistic for testing significant differences between paired combinations of fuzzy error matrices for the whole dataset is listed in table 9.

User’s accuracy, producer’s accuracy, estimated standard deviations of the user’s accuracy and producer’s accuracy for the whole datasets are shown in figures 5 to 8 respectively. Also, conditional kappa coefficients and their corresponding standard deviations for the whole datasets are shown in figures 9 to 12. In all, trees and bare soil recorded higher accuracies than shrubs and herbaceous plants. This is attributed

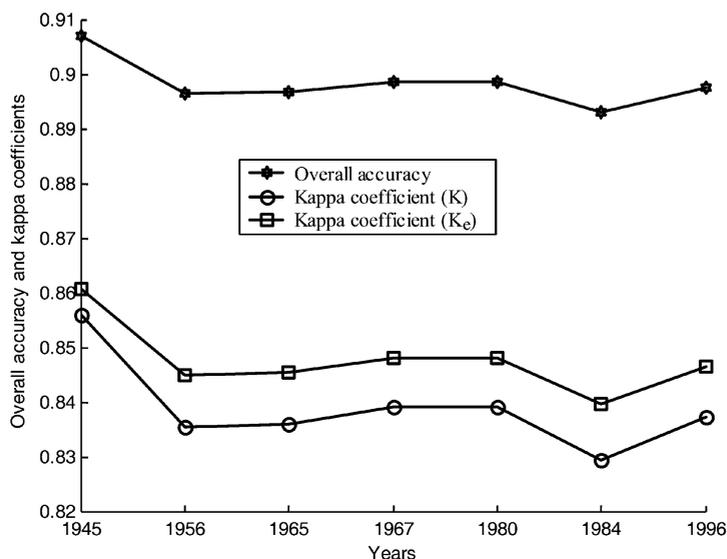


Figure 3. Overall accuracy and kappa coefficients for the seven datasets.

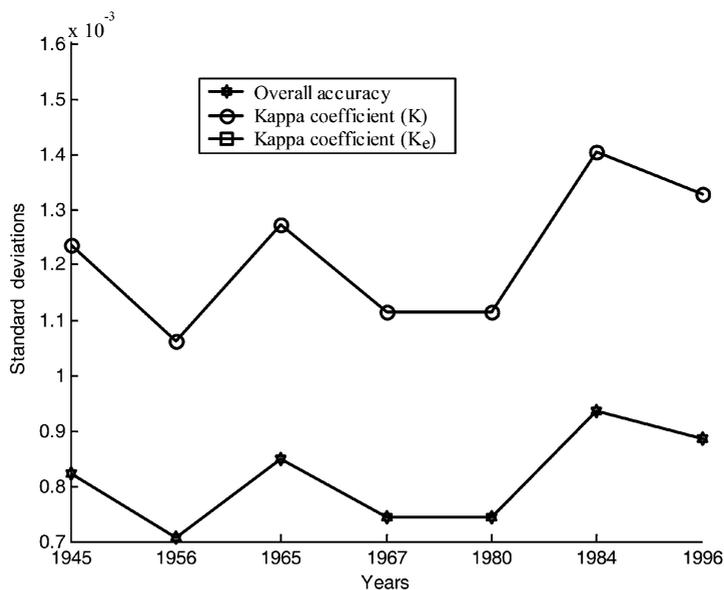


Figure 4. Standard deviations for the overall accuracy and kappa coefficients.

to the fact that the classes of trees and bare soil have less mixture than the class of shrubs and herbaceous plants.

6. Discussion

The method described in this paper relies on classification into broad classes using reflectance from individual pixels, and has been tested with a small number of classes. The application of this method for complex land cover categorization has not, however, been tested, but must naturally follow the same procedure as described here. Surely, the fuzzy classification technique has been successfully applied to complex land cover categorization. However, a potential difficulty might arise in very complex land cover cases where the values of class centroids of some classes are very close. In such cases adequate care must be taken in the determination of appropriate class centroids for the different categories by using suitable heuristic techniques in combination with a powerful image display system (i.e. Erdas Imagine software) to achieve very precise labelling of the classes in the complex scenario.

Table 9. Z statistics for testing significant differences between paired combinations of fuzzy error matrices for the whole dataset.

	1945	1956	1965	1967	1980	1984	1996
1945	–	0.425	0.401	0.344	0.344	0.516	0.370
1956		–	–0.006	–0.079	–0.079	0.123	–0.034
1965			–	–0.069	–0.069	0.124	0.027
1967				–	0.000	0.196	0.041
1980					–	0.196	0.040
1984						–	–0.149
1996							–

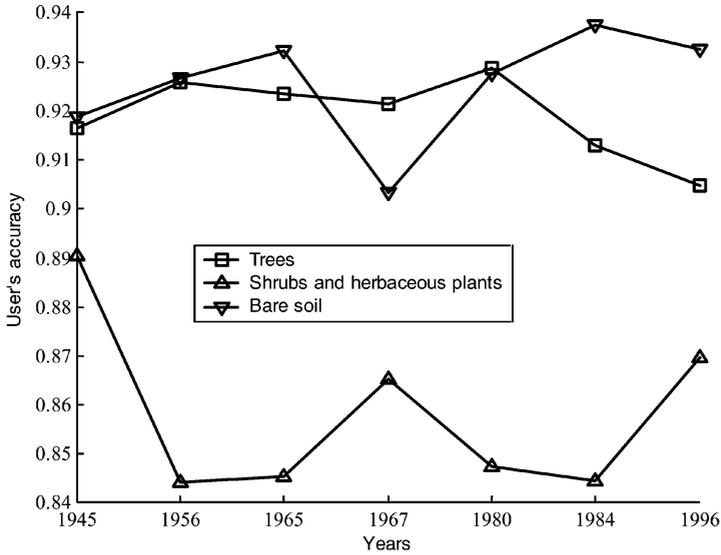


Figure 5. User's accuracy for the seven datasets.

The procedure described in this work is aimed at change detection of scenes captured by image sensors at different times. Therefore the entire procedure (classification and accuracy assessment of classification) should be carried out for each image in order to provide the basis for inter-comparison between one image and another. Different sites located in the same image share the same characteristics and properties of that image.

All algorithms used in this work are polynomially bounded and are well solved. Time complexity of stages described here depends mostly on the size of the image to be processed. Each component of the analysis processed by programs scripted in

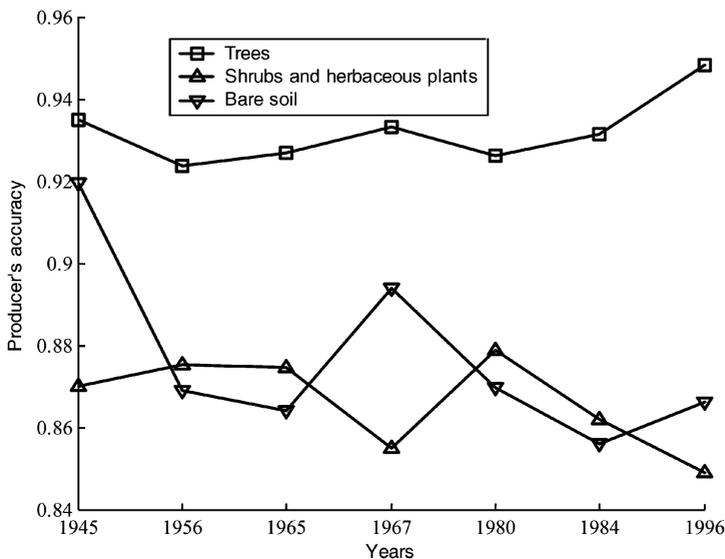


Figure 6. Producer's accuracy for the seven datasets.

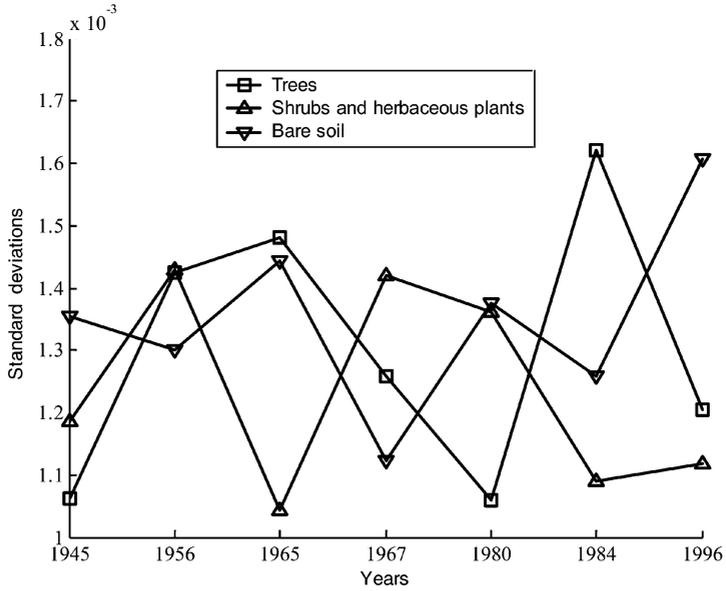


Figure 7. Standard deviation of user's accuracy.

Matlab version 6.5 and running on a PC (Pentium 4 with 1.2 GB RAM) takes an average of 3 seconds for an average image size of 1000 pixels by 1000 pixels.

The outcome of empirical investigation in this paper using real datasets has shown the applicability and simplicity of the proposed procedure of classification and assessing the accuracy of classification in situations where no ground data are available. After classification and accuracy assessment, change analysis and statistical tests could then be applied using the products of classification and

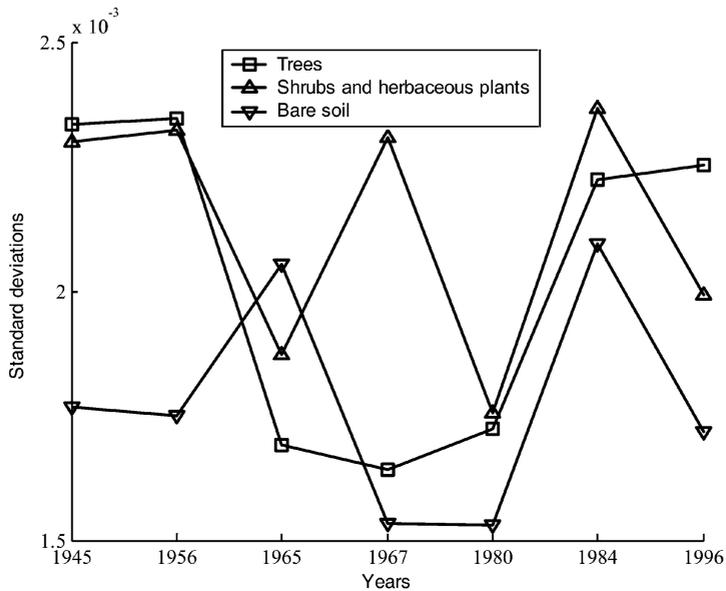


Figure 8. Standard deviations of producer's accuracy.

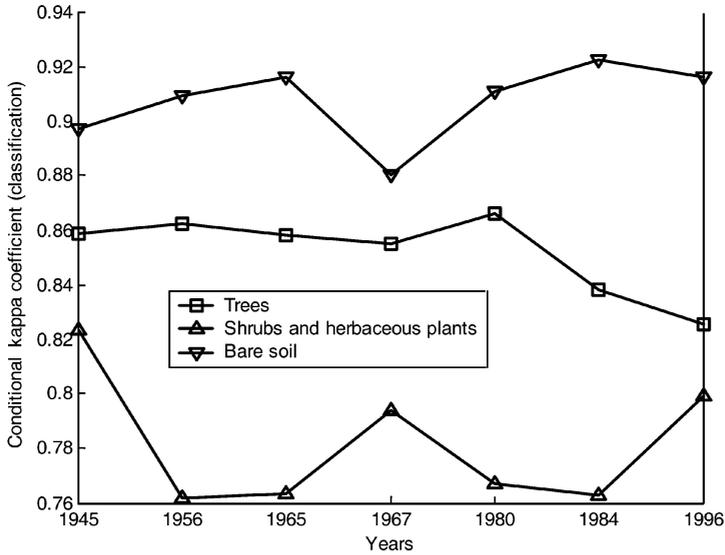


Figure 9. Conditional kappa coefficient (classification) for the seven datasets.

accuracy assessment. It is to be emphasized that the accuracy assessment procedure proposed in this work is suitable for situations where crisp product of classification is desired.

The proposed procedure shares the advantages and limitations of unsupervised classification techniques. In particular, the proposed procedure relies on the capability of the analyst to provide accurate labelling of classes after classification of the base dataset. Nevertheless, this is not different from the challenges encountered in a classical supervised classification procedure, where the analyst is expected to provide training data and reference data for classification and accuracy assessment

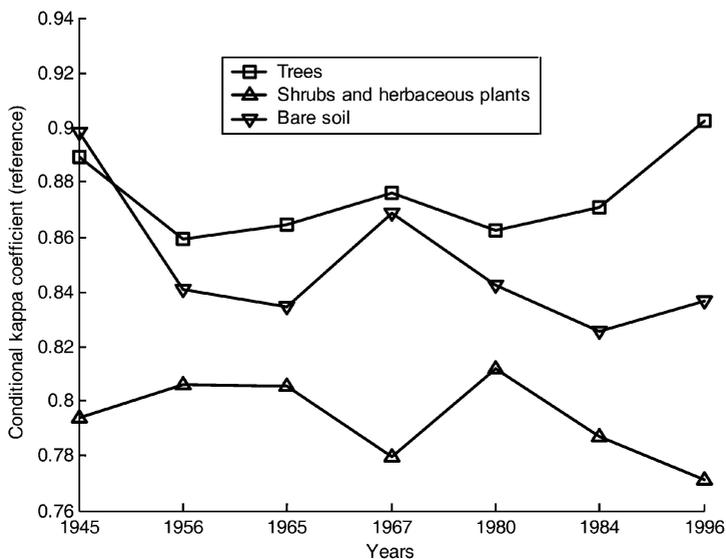


Figure 10. Conditional kappa coefficient (reference) for the seven datasets.

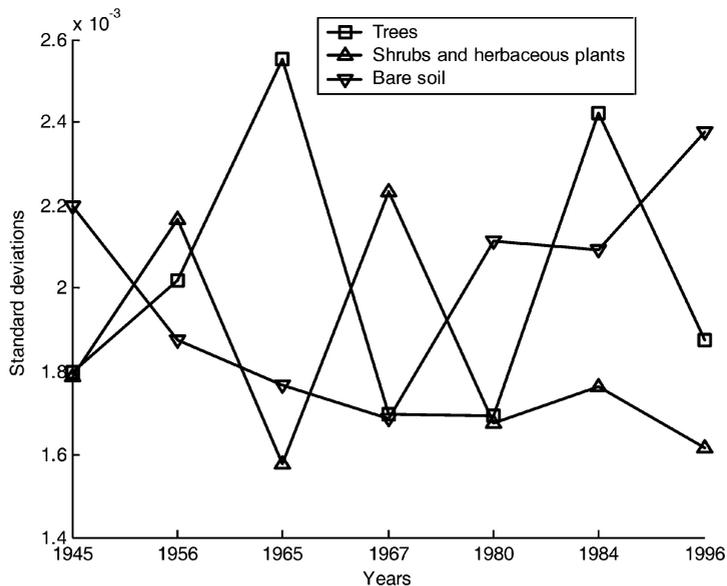


Figure 11. Standard deviations of conditional kappa (classification).

respectively. However, an important issue in the application of the proposed procedure for change detection analysis is that a high level of consistency is maintained in the classification and post classification labelling of all the datasets. Consistency, in this case, is largely enhanced by the application of fuzzy supervised classification for the rest of the datasets using outputs of classification of the base dataset.

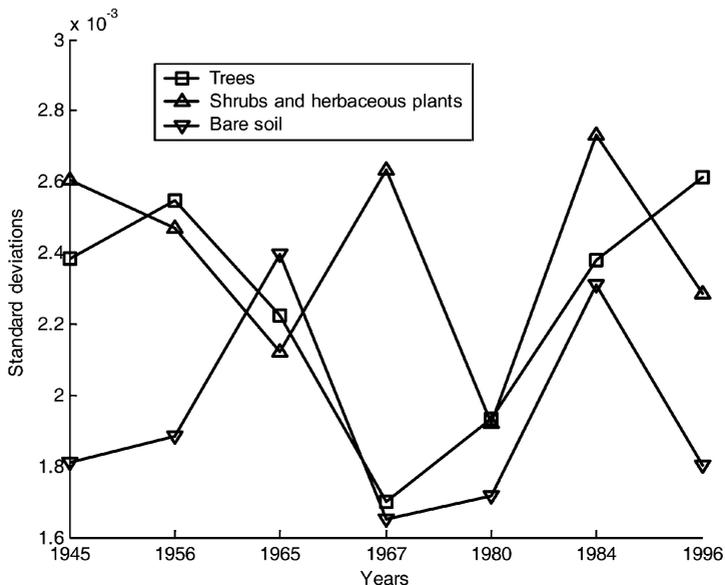


Figure 12. Standard deviations of conditional kappa (reference).

Arguments may be raised on the suitability of the term 'accuracy assessment' with reference to the proposed procedure, since the reference data itself is the output of fuzzy classification, and may not necessarily be an accurate representation of reality. Again, this is not different from the argument put forward against classical accuracy assessment procedures where the reference data are mostly derived from some sort of classification. In the classical accuracy assessment procedure, more precise data are used as reference data, which is equivalent in our procedure to the use of more accurate membership grades as reference data for the accuracy assessment of hard classification products. In addition, membership grades of fuzzy classification have been shown to have strong correlation with true class proportions.

In the absence of ground data, the proposed procedure provides a suitable and reliable alternative to the situation where no accuracy assessment of classification is performed at all.

7. Conclusion

This paper presents methods of classification of historical aerial photographs and accuracy assessment of classification products for change analyses using fuzzy classification technique.

Most importantly, a method of construction of a fuzzy error matrix for the assessment of classification accuracy in the absence of ground data, when crisp products of classification are desired, is described. The method of bootstrap resampling for the computation of standard errors of accuracy measures derived from the constructed fuzzy error matrix has also been demonstrated. The applicability and simplicity of these methods have been illustrated using real datasets. Results show the benefits of the combined use of the unsupervised/supervised FCM algorithm and bootstrap resampling technique for the classification and accuracy assessment of historical aerial photographs for change analysis. These methods require no *a priori* training data and no specific sampling design; they only require accurate *a posteriori* labelling of classes after classification, and consistency in the processing of all datasets involved in the change analysis. It is expected that these methods would be useful to classification and accuracy assessment applications where training data and ground data are impossible to obtain.

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