The Map Comparison Kit

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Abstract

Comparing maps is an important issue in environmental research. There are many reasons to compare maps: (i) to detect temporal/spatial changes or hot-spots, (ii) to compare different models, methodologies or scenarios, (iii) to calibrate, validate land-use models, (iv) to analyse model uncertainty and sensitivity, and (v) to assess map accuracy. This paper addresses the quantification of map similarities and dissimilarities using the Map Comparison Kit (MCK) software. Software and documentation are publicly available on the RIKS website free of charge (http://www.riks.nl/MCK/). The main focus is on ‘categorical’ or ‘nominal’ maps. Four different nominal map-comparison techniques are integrated in the software. Maps on ordinal, ratio and interval scale can be dealt with as well. The software is unique in having two map comparison techniques based on fuzzy-set calculation rules. The rationale is that fuzzy-set map comparison is very close to human judgement. Both fuzziness in location and fuzziness in category definitions are dealt with in the software.

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Software availability

Name of the software: Map Comparison Kit
Developer: Research Institute for Knowledge Systems (RIKS)
Contact address: RIKS BV, P.O. Box 463, 6200 AL Maastricht, Netherlands
E-mail: ahagen@riks.nl
Year first availability: 2004
Hardware required: A platform to run MS Windows 1998, 2000, NT or XP
Size of the maps: The software sets no limits on the size of the maps. The limits are set by the user’s PC

Software required: None
Program language: Geonamica
Program size: 17 MB
Availability and cost: Available and free of charge
Download from: http://www.rivm.nl/milieu/modellen or http://www.riks.nl/MCK/

1. Introduction

Growth of high-resolution spatial modelling, geographical information systems and remote sensing has increased the need for map-comparison methods. The importance of map-comparison methods has been recognized and has stimulated growing interest among researchers (Monserud and Leemans, 1992; Metternicht, 1999; Winter, 2000; Pontius, 2000; Pontius and Schneider, 2001; Power et al., 2001; Hagen, 2003; Pontius et al., 2004).

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In general, maps are compared for a number of reasons. We name four of these reasons. First, we may want to compare maps generated by models under different scenarios and assumptions. As for a set of land-use maps we are interested in questions such as ‘how similar are the maps?’ or ‘for which land-use category are both maps most dissimilar?’ Second, we may want to detect temporal changes. Since many maps have a temporal dimension, a spatio-temporal analysis may yield insight into economic and demographic developments.

Third, we may want to calibrate/validate land-use models. Land-use models such as the Environment Explorer (Engelen et al., 2003) and the Land Use Scanner (Borsboom-van Beurden et al., 2002) generate land-use maps starting with an observed land-use map. How well do these models predict future developments and how can we optimize model output to unknown parameters in the model? For such calibration problems we need an objective measure for map (dis)similarity. In fact, map comparison may be seen as finding a Goodness-of-fit measure.

Finally, we may want to perform uncertainty and sensitivity analyses. There are many sources of errors in maps. Comparing model output to a reference map allows such errors to be detected and quantified. The same holds for the accuracy of satellite-based maps. In fact, calibration is a form of uncertainty analysis.

In this article we review a software package that can be used for maps on different measurement scales, i.e. maps on nominal, ordinal, interval or ratio scales (definitions from Stevens, 1946). Nominal maps have the simplest and most elementary type of measurement scale, where objects/categories are only discriminated from another. For these maps comparison is most complicated: e.g., how can we compare the nominal object ‘grassland’ with ‘residential’, or ‘glasshouses’ with ‘recreational’? At the same time we are looking for an exact quantification of differences between maps containing such categories.

Also ordinal maps are dealt with. Ordinal maps are characterized by the property of order: we specify both the differences between objects/categories and the direction of those differences. Maps on interval and ratio scale are based on continuous variables. They allow for exact quantification of differences. The difference between an interval scale and a ratio scale is the presence of a fixed zero point in the latter scale (e.g., Fahrenheit temperatures are on an interval scale while Kelvin temperatures are on a ratio scale).

The software introduced here incorporates four nominal map-comparison techniques, denoted as ‘Per category’, ‘Cell by cell’, ‘Fuzzy Inference System algorithm’ and ‘Fuzzy Set algorithm’, one ordinal method, denoted as Fuzzy Set algorithm – advanced, and six comparison methods for interval and ratio scale maps. The rationale behind this new software is the combination of standard cell by cell map comparison (the Kappa statistic and newly derived variants on Kappa) and recent developments in fuzzy-set map comparison (the Kappa fuzzy). Up to now there is no software available for the latter techniques. The strong side of fuzzy map comparisons is that it resembles the way human observers compare maps.

A simple example is that of two checkerboards, with one board turned around 90°. If we regard the boards as maps with only two categories (‘black’ and ‘white’), a cell by cell comparison will reveal that both maps are totally different. However, a human observer would judge both patterns as highly similar. The same holds for fuzzy similarity. An in-depth experiment showing the similarity between fuzzy comparison and human judgement has been given by Hagen (2002b) for an Internet experiment showing 10 map pairs (Kuhnert, 2002). One hundred and twenty-seven participants gave their judgement of map similarity (a figure between 0 and 1, 0 = totally different and 1 = totally equal). The ‘fuzzy Kappa’, which we will describe in Section 3, was strongly correlated to the human judgements ($R^2 = 0.88$).

The software is called the Map Comparison Kit, or MCK for short. The MCK is a software package for ‘state of the art’ map comparison developed by the Research Institute for Knowledge Systems (RIKS) and the Netherlands Environmental Assessment Agency (MNP — RIVM). The MCK software was originally designed for analysis of land-use maps. However, the software is employable for many more GIS applications than these types of models (remote sensing, ecological models predicting the presence of plant or animal species, etc). In fact, the software yields general methods for pattern recognition.

A humoristic example of the latter ability is given in Fig. 1. Here two ‘maps’ are analysed which look very similar but contain 15 major differences. Furthermore, the maps are not co-registered because we shifted the complete original second map a few grids to the right (not visible for a human observer!). The fuzzy difference map corrects for the lack on co-registration and easily identifies the 15 differences.

This article gives an overview of the MCK software (Section 2.1). We give examples of the software screens and how to choose different scales and methods (Section 2.2). The rationale between different approaches present in the software is dealt with in short (Section 3). Then, we present an application for land-use maps in Section 4. Finally, an evaluation of the software along with plans for the future is given in Section 5.

We note that this article is not meant as a research article on map-comparison techniques. The scientific background of MCK has been published by Hagen (2002a, 2002b, 2003) and Power et al. (2001), and has been summarised by Visser (2004).
2. The Map Comparison Kit

2.1. Software

The first version of the Map Comparison Kit dates back to 1992 and was intended for analysing a series of land-use maps. From 1992 onwards, the tool was steadily further developed as part of RIKS projects for various institutions. The latest extension of the Map Comparison Kit was developed in collaboration with and by order for the account of the Netherlands Environmental Assessment Agency (MNP – RIVM).

The Map Comparison Kit was designed for analysis and comparison of raster maps, as illustrated in Fig. 2. Maps may be on nominal, ordinal, interval or ratio scales. The software can also handle mixtures of nominal and ordinal scales.

Besides map comparison the MCK offers options to import/export comparative file formats (ArcInfo, Idrisi), organize and visualize raster maps. Standard windows copy functionality allows to paste maps and statistics in, for example, an MS-Office document in Word. For further understanding of the methods a number of map data sets have been added to the MCK software. Please see Visser (2004) for an analysis of these data sets. Software and documentation can be downloaded from http://www.rivm.nl/milieu/modellen.

In addition to the stand-alone version, a Map Comparison Module, containing the ‘Cell-by-cell’, the ‘Fuzzy Inference System’ and the ‘Fuzzy Set’ algorithm is available (Uljee, 2003). The module can be incorporated into GIS packages like ArcGis-8 and has the advantage that

- it does not require the export and import maps,
- it can employ the attractive features from GIS, such as zooming in on a small area and then carrying out the calculations within this sub-area,
- it facilitates an easy programming of a batch environment for MCK calculations where many map pairs occur.

2.2. Handling different measurement scales

The main window to select a comparison method is shown in Fig. 3. There are 10 comparison methods in total, among the four measurement scales described in Section 1. The upper box is for nominal maps and applies to four methods, varying from ‘Per category’ and ‘Cell-by-cell’ to ‘Fuzzy Inference System’ and ‘Fuzzy Set algorithm’. The rationale behind these fuzzy methods is given in Section 3.

The ‘Fuzzy Inference System’ has an advanced screen where default settings may be altered. This screen is shown in Fig. 4. The upper part of the screen is for choosing fuzziness in location, the lower part for introducing fuzziness in category definitions:

- The calculation of fuzziness of location is based upon the notion that the fuzzy representation of a cell depends on the cell itself and, to a lesser extent, also the cells in its neighbourhood. The extent to which the neighbouring cells influence the fuzzy representation, is expressed by a distance decay function. Three of such functions are shown in Fig. 5: a cone or ‘linear decay’ (defined by slope), an exponential decay (defined by halving distance) or a 3-D Gauss curve (defined by variance), see Bandemer and Gottwald (1995). Which function is most appropriate and which radius of neighbourhood one should choose, depends on the nature of the uncertainty, vagueness of the data and the observer’s tolerance for spatial error. From a theoretical point of view, there is no best alternative. Hence, it is worthwhile to experiment with size and form of the function.
The Category Similarity Matrix can be applied to nominal maps where category definitions are (partly) unequal (i.e. maps with unequal legendas) or vague. In fact, we may perform a semantic rather than a geometric map comparison by using vague category definitions. Vagueness can be introduced by setting off-diagonal elements in the Category Similarity Matrix to a number between 0 and 1. We note here that the approach above is, in principle, not meant for semantic map comparisons. References on semantic map comparison are Rodriguez et al. (1999) and Kokla and Kavouras (2001).

Ordinal maps can be examined with the Fuzzy Set algorithm using the Category Similarity Matrix (Fig. 4). In fact, we define a nominal set of maps where adjacent categories have vague transitions. The off-diagonal elements can be used to define how similar adjacent categories are: e.g., we may want to make the two categories, ‘sparse residential’ and ‘dense residential’, more or less similar by applying a value of, say, 0.5. A value of 1.0 would make both categories totally equal and would in fact define the new category, ‘total residential’.

We note that the use of the Category Similarity Matrix allows us to handle pairs of maps, which are partly nominal and partly ordinal. As in the example above: ‘residential’ categories have an ordinal character, while other categories are nominal.

Another example. Suppose we have an ecological model predicting the presence (‘1’) or absence (‘0’) of a particular plant species by chances on a gridded map. Chances are expressed in the following categories: the chance of a plant being present in a particular grid lies between 0.0 and 0.25 (category 1), between 0.25 and 0.50 (category 2), between 0.5 and 0.75 (category 3) or between 0.75 and 1.0 (category 4). Clearly, adjacent categories are similar. We want to compare the chance map for 2004 with a predicted map for 2020. To employ the similarity between adjacent categories, we might choose the following Category Similarity Matrix:

\[
\begin{pmatrix}
1.00 & 0.70 & 0.40 & 0.10 \\
0.70 & 1.00 & 0.70 & 0.40 \\
0.40 & 0.70 & 1.00 & 0.70 \\
0.10 & 0.40 & 0.70 & 1.00
\end{pmatrix}
\]

Since choosing values in the matrix is subjective, it has to be selected on the basis of a priori insights. We advise to experiment with different settings and to evaluate the sensitivity of map similarity (Kappas) to these settings. If more than one pair of maps are
involved, it could be advantageous to find one matrix setting for all pairs of maps.

When we are dealing with maps on interval or ratio scales, we may choose a method from methods 5 to 10 (in Fig. 3), and exploit the character of specific continuous variables: subtracting or dividing values for identical grid cells. We then get result maps showing map differences on a continuous scale. If the values in both maps are denoted by $y_{ij}$ and $x_{ij}$ with $i,j$ the coordinates of a specific grid, the differences $d_{ij}$ for methods 5 to 10 are defined as:

- Method 5: $d_{ij} = y_{ij} - x_{ij}$
- Method 6: $d_{ij} = \frac{|y_{ij} - x_{ij}|}{\max (|y_{ij} - x_{ij}|)}$
- Method 7: $d_{ij} = (y_{ij} - x_{ij})\cdot \max \frac{y_{ij}}{(y_{ij} - x_{ij})}$
- Method 8: $d_{ij} = \frac{|y_{ij} - x_{ij}|}{\max (|y_{ij} - x_{ij}|)}$
- Method 9: $d_{ij} = \frac{y_{ij}}{x_{ij}}$
- Method 10: $d_{ij} = \frac{|y_{ij}|}{x_{ij}}$

We note that these six operations are not exclusive for the MCK software and can be performed by most GIS packages. The methods have been added to make the MCK software more complete.

As an alternative approach we may transform the continuous variable to disjunct categories and, subsequently, explore map similarity with the Fuzzy Set algorithm (by choosing a proper Category Similarity Matrix). Of course, some information will be lost by the transformation.

3. Map-comparison methods

Hereafter we describe the map-comparison ideas underlying the methods contained in the MCK software and described in Hagen (2002a). For theoretical details we refer to Pontius (2000), Power et al. (2001) and Hagen (2002b, 2003).

3.1. Visual versus automated map comparison

For most purposes visual, human comparison of maps outperforms automated procedures. When comparing maps, the human observer automatically takes many aspects into consideration. Local, but also global similarities, logical coherence and patterns are recognised. Map-comparison software methods usually capture single aspects, while overlooking others. Furthermore, these methods generally lack the flexibility to switch from one aspect to the other when the data require so. An example of this rigidity is the simple cell-by-cell comparison of two checker boards as described in Section 1.

Despite the clear disadvantages, in the following situations automated map comparison is preferred above visual map comparison:

- Where time and human effort can be saved.
- Where objectivity and repeatability is desired, since automated procedures are explicitly defined. The method can therefore be analysed and evaluated,
and the results verified. A visual map comparison will always be subjective and often intuitive, so that the outcome of a visual map comparison may depend on the person performing the comparison.

- Where most comparison techniques fall short, recent developments in fuzzy-based map comparison have shown that these methods highly reflect the way humans look at maps.

The general philosophy behind MCK software is that instead of visual and automated map comparisons excluding each other, they actually yield complementary insights. The same holds for map comparison based on cell-by-cell similarity (Section 3.2) and map comparison based on fuzzy-set calculation rules (Section 3.3).

3.2. Cell-by-cell map comparison

The Kappa statistic for nominal maps was introduced by Cohen (1960). Often used to assess the similarities between observed and predicted results, it is not only applied to geographical problems...
Kappa is a measure of similarity between two maps based on a contingency table (shown in the lower part of the right panel of Fig. 9). In essence, Kappa is based on the percentage of agreement between two maps, corrected for the fraction of agreement that can be expected by pure chance. Recent extensions of Kappa are the ‘Kappa location’ (Pontius, 2000) and the ‘Kappa histo’ (Hagen, 2002a). These statistics are sensitive to respective differences in location and in the histogram shape of all the categories. In the software ‘Kappa location’ is abbreviated as KLoc, and ‘Kappa histo’ as KHisto.

Kappa, KLoc and KHisto are connected through the multiplicative relation

\[ \text{Kappa} = \text{KLoc} \times \text{KHisto} \]

Thus, given a fixed value for Kappa, KLoc will increase if KHisto decreases, and vice versa. Furthermore, if categories in both maps lie at identical locations, we have KLoc = 1.0, and Kappa = KHisto. If the frequency of categories in both maps is equal, we have KHisto = 1.0 and Kappa = KLoc. Examples from practise have been given in Visser (2004).

After the calculation of Kappas one may want to determine whether the observed value was greater than the value which would be expected by chance or one may want to compare Kappas from different map comparisons. To do so we need to know the significance of Kappa. Formulae are given in Siegel and Castellan (1988, p. 289). Confidence limits for Kappa (and KHisto/KLoc) are not incorporated in the present version of the MCK software. In an update of the software we will add confidence limits to Kappa, KHisto and KLoc, based on Monte Carlo simulation of randomized maps which are derived from the original maps. We note that Kappa confidence limits should be handled with care as discussed by Foody (2004).

3.3. Fuzzy-based map comparison

The fuzzy-based map-comparison method was primarily developed for use in the calibration and validation process of cellular models for land-use dynamics. The method is based on fuzzy-set calculation rules (Zadeh, 1965). Several authors have addressed the potential of fuzzy-set theory for geographical applications (Cheng et al., 2001; Fisher, 2000). In the past, fuzzy-set theory was used to assess the accuracy of map representations and for map comparisons (Metternicht, 1999; Power et al., 2001).

The objective of fuzzy-based map comparison is to find a method that to some extent mimics human comparison and gives a detailed assessment of similarity. The method is primarily directed at comparing nominal and ordinal raster maps, as illustrated in Section 4. The assessment results are spatial, with (dis)similarities presented on a gradual scale.

Additionally, an overall figure for similarity, the Fuzzy Kappa statistic, is aggregated from the detailed spatial results (fourth method in Fig. 3 and right panel of Fig. 10). The Fuzzy Kappa, or Kfuzzy in short, is similar to the traditional Kappa statistic: the expected percentage of agreement between two maps is corrected for the fraction of agreement statistically expected from randomly relocating all cells in both maps.

A simple illustration for the difference between the traditional Kappa and Kfuzzy is given in Fig. 6. Fig. 6A demonstrates this with two pairs of maps. The Kappa statistic and the Percentage-of-Agreement are identical for both pairs, even though a human observer would consider the first pair (a) to be more similar than the second pair (b). The effect of applying Kfuzzy is illustrated in Fig. 6B. It shows that the tolerance for small spatial differences indeed leads to a higher similarity of the first pair of maps. For details please see Hagen and Uljee (2003) and Hagen (2003).

Another promising approach is that of Hierarchical fuzzy pattern matching (third method in Fig. 3). This approach is based on the comparison of overlapping polygons (i.e. groups of concatenated cells belonging to the same category). Polygons are then compared on the basis of a number of properties, such as size and overlap. These comparisons are based on a so-called Fuzzy Inference System (FIS). A global agreement value can be derived by the fuzzy summation of the local matching. This global agreement, comparable to the Kfuzzy statistic, is denoted as Global matching index. The theory behind hierarchical fuzzy pattern matching is fully described by Power et al. (2001). At the moment the fuzzy inference approach misses the functionality as shown in Fig. 4 for the fourth method. Therefore, we prefer to use Kfuzzy statistics (fourth method in Fig. 3) rather than the FIS approach (third method in Fig. 3).

3.4. Map similarity measures other than Kappa

The concept of the Kappa statistic (and variants thereon) plays a central role in the MCK software. The reasons for choosing this statistic are threefold:

- It has been extensively applied in research fields such as land-use modelling, remote sensing and ecological modelling.
The chance correction in Kappa’s is attractive: because of this correction we may compare Kappa’s (and its variants as well) across pairs of maps. Suppose, for example, that we have two binary map comparisons yielding an identical percentage of agreement (PA) of, say, 70%. Are both pairs of maps equally similar? They are, if the frequencies of categories are equal across all four maps. If categories 1 and 2 in the first pair both have frequencies of 50% and if in the second pair category 1 has a frequency of 10% and category 2 a frequency of 90%, the chance correction is 50% for the first pair and 82% for the second pair. Thus, a PA of 70% in the first pair is better than what could be expected by chance (50%). For the second pair a PA of 70% is worse (82% by chance).

Hagen (2002b) has shown by a heuristic map comparison exercise from the Internet (Kuhntert, 2002) that Kfuzzy estimates compare very good to human judgement (127 people rated the similarity of 10 sets of maps with a number between 0.0 and 1.0).

Thus, applying Kfuzzy, we have a measure which is close to the way humans compare maps.

However, there are other measures for map similarity than Kappa, and some authors doubt the practical value of Kappa. Indeed, a measure with chance correction may not be advantageous under all circumstances. Other measures were discussed by Cohen (1968); Turk (2002) and Foody (2004). Pontius (2002) suggests to choose ‘disagreement due to quantity’ and ‘disagreement due to location’, as better alternatives for KHisto and KLoc.

However, as explained above, the rationale for choosing Kappa is not that it is the ‘best’ measure for all applications. In fact we should define the term ‘best’; it is not an absolute criterion. It depends on the specific goals of the user. For us, the Kappa statistic has attractive properties, which are useful for our applications. Moreover, the Kfuzzy statistic scores very good if we define ‘best’ in terms of ‘similar to human judgement’. Finally, the fuzzy approach is unique in
having the possibility of defining both vagueness in location and vagueness in category definitions.

4. Comparing land-use maps

This section provides an application example of the use of the MCK software. We use two land-use maps for the Netherlands, on a 500 by 500 m grid. Both maps are on a nominal scale with 7 categories. One map is for a past situation (1995) and the other is a model prediction for the year 2020. More examples of map comparisons on other measurement scales are given in Visser (2004).

4.1. Simulating land use

To support planning systems in the Netherlands, and to evaluate the consequences of spatial development, e.g. urbanization, it was decided in 1996 to jointly develop an instrument for the prediction of future land-use patterns for valuable landscapes, nature areas, the environment and water systems. This led to the development of the Land Use Scanner. The aim of the Land Use Scanner is to elaborate different scenarios by integrating and allocating exogenous land-use claims originating in sectoral models, such as those for housing and employment. The resulting future land-use configurations may serve in turn as input for other models, e.g. hydrological and ecological models. The Land Use Scanner should be placed in the tradition of equilibrium models that use micro-economic-theory-based assumptions on supply, demand and price setting. References are Schotten et al. (2001) and Borsboom-van Beurden et al. (2002).

Visser (2004) analyses two scenario simulations for the year 2020: the ‘Country of Cities’ scenario and the ‘Country of Flows’ scenario. According to the ‘Country of Flows’ policy concept, future land use will be directed to the optimal functioning of international streams, both in economic and ecological contexts. This goal determines the choice of future locations for residential, work and nature areas. The economic ‘streams’ are directed to the road network and the ecological ‘streams’ to the water network. The main challenge here is combining these two streams. Urbanization will be concentrated along a few main transport axes in the form of a ‘string of beads’. In contrast, the ‘Country of Cities’ scenario foresees new residential areas with high intensities arising in and around existing cities.

The actual land-use map in 1995 and the Land Use Scanner simulation for the year 2020 according to the ‘Country of Flows’ scenario are given in Fig. 7.

4.2. Map comparison

The ‘Per category’ comparison method is illustrated in Fig. 8 for the categories ‘Residential’ and ‘Agricultural’. The blue colour in the left panel shows the predicted ‘string of beads’ for ‘Residential’ in 2020.
Fig. 8. Map differences for two single land-use categories using the first option ‘Per Category’, shown in Fig. 3. The left panel is for ‘Residential’, the right panel for ‘Agricultural’. Map 1 = situation 1995; map 2 = simulation 2020.

Fig. 9. Equal–unequal map and corresponding Kappa statistics, using the second option ‘Cell by cell’, shown in Fig. 3.
(= map 2), while the right panel shows in red (= map 1) that ‘Agricultural’ has disappeared at the expense of ‘Residential’.

The equal—unequal map, in Fig. 9, is obtained as a result of applying the ‘Cell by cell’ method. The colour green points to cells in both maps with identical categories, the colour red to cells with unequal categories. The right panel shows the Kappa statistics. First the overall statistics are shown (Kappa, Fraction correct, KLoc and KHisto, as described in Section 3). Then, Kappa statistics are shown per category. This means that we simplify both maps in Fig. 7 to maps with only two categories: ‘Residential’ versus ‘Other’, ‘Industrial/Work’ versus ‘Other’, etc. Next, Kappas are calculated for these ‘binary’ maps. The lower matrix shows the contingency table for the seven categories, ‘Residential’, ‘Industrial/Work’, ‘Infrastructure’, ‘Agricultural’, ‘Forest’, ‘Nature’, and ‘Water’.

From the overall Kappas we see that the KLoc value (0.87) is less than the KHisto value (0.92), signifying that both maps differ more in the overall frequency of the various categories than in the location of categories.

The binary comparison of categories reveals minimal changes for ‘Water’. All Kappas are found near the maximum value 1.0 (Kappa = 0.97, KLoc = 0.99 and KHisto = 0.98). Clearly, no hydrological changes are foreseen. Kappa for ‘Residential’ is found to be relatively low (0.48), a result completely due to the different location of categories (KLoc = 0.49 and KHisto = 0.99), easily explained by the location of the scenario ‘Country of Flows’. Finally, changes for ‘Infrastructure’ are maximal. All Kappas are small (Kappa = 0.20, KLoc = 0.66 and KHisto = 0.31) due to such projected infrastructural changes in the Netherlands as the result of denser rail freight transport.

The left panel of Fig. 10 shows the result map of the Fuzzy Set algorithm, using default settings for the MCK software (exponential decay with a neighbourhood radius of four cells). It is clear that the fuzzy approach reveals many more nuances between the two maps than the simple equal—unequal map. The right panel shows the Kfuzzy statistics corresponding to the maps being compared.

5. Final remarks

Here we have presented map-comparison software, in which both traditional and advanced techniques have been integrated. To our knowledge, no other comparative software package is available at present. Only the traditional Kappa statistic is incorporated in statistical packages such as SAS and SPSS, and some digital image processing packages.

We have paid special attention to the handling of nominal and ordinal maps in view of the sparse existing methods in this area. In fact, the software implementation for ordinal map-comparison techniques is unique.
The handling of maps on interval/ratio scales is also part of the software and has been added for completeness (many GIS packages can perform the operations given in Section 2.2 as well).

The application in Chapter 4 has illustrated that both cell-by-cell comparison and fuzzy-set map comparison are able to grasp the characteristics of map differences, although in different ways. To our experience, the combination of these approaches yields an ideal way of analyzing maps and map differences (cf. examples in Visser, 2004).

Our experiences with the Map Comparison Kit software have been very positive. The software is easy-to-use and limits are only set by the memory conditions of the PC. However, the software is not static and we are planning to improve the software.

The software will be extended in the following ways:

- Creating a batch environment around the MCK software for handling huge amounts of maps would be helpful. In some environmental applications over 150 pairs of maps have to be compared and it is too time consuming to do this ‘by hand’.
- For some analyses aggregating both maps to a coarser grid would prove interesting (Pontius, 2002; Pontius et al., 2004). After that, we want to analyse differences through use of map statistics. A different problem will also be treated, that of two maps with unequal grid sizes.
- In practice we have to compare maps having unequal legends. In some cases a re-classification of categories would be sufficient to make the legends the same (by use of the Category Similarity Matrix, shown in Fig. 4), but this will not be sufficient in all cases.
- Kappa, KLoc, KHisto and Kfuzzy are not calculated with accompanying uncertainty limits within the MCK software. Advantage of having such limits is that two Kappas could be tested for significance. Examples (and warnings) are given by Foody (2004). Therefore, Kappa, KLoc, KHisto and Kfuzzy will be extended with their respective uncertainty estimates. We will choose a Monte Carlo approach, since this approach will apply to all four Kappa measures.
- It will be possible to apply the fuzzy approach directly to maps on interval or ratio scale. The ‘transform step’ shown in Fig. 3, will become redundant, and no information will be lost anymore by transforming these maps to ordinal maps.

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References


