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THE POTENTIAL OF FUZZY LOGIC FOR QUANTITATIVE LAND COVER CHANGE ANALYSIS BASING ON HISTORICAL TOPOGRAPHIC MAPS

Abstract: This paper describes an approach that allows to reduce error propagation when comparing historical topographic maps. By linking the fuzzy set theory with simple map algebra and Kappa statistics, the uncertainty resulting from dissimilar quality of the maps can at least be partly eliminated and a distinction between 'true' and 'false' land cover changes can be made.

Keywords: old topographic maps, land cover change, fuzzy sets, Kappa statistics, quantitative analysis

1. INTRODUCTION

The map comparison is a vital process in detecting spatial-temporal changes in landscape pattern. The visual comparison of maps representing different moments in time is to some extent subjective, but can lead to many interesting observations of a qualitative character. The quantitative land cover change investigations are more objective but usually time consuming, as the land cover data need to be scanned, georeferenced and vectorised at first.

One of the most popular methods for quantitative pairwise comparison of raster maps with categorical legends is so called *Cell-by-cell*, which considers each pair of cells on two maps to be either equal or not equal. For quantifying an overall similarity of two maps *Kappa* statistics (Cohen, 1960) is often applied:

$$Kappa = \frac{P(A) - P(E)}{1 - P(E)}$$

P(A) –fraction of agreement,

P(E) – expected agreement based on random location subject to the observed distribution.

The standard *Kappa* can be split in two: *Kappa Histo* (similarity of quantity, referring to the total number of cells taken by each category of the legend; Pontius, 2000) and Kappa Location (similarity of location, referring to the spatial distribution of the different categories over the map; Hagen, 2002):

$$KappaLoc = \frac{P(A) - P(E)}{P(\max) - P(E)}$$

$$KappaHis = \frac{P(\max) - P(E)}{1 - P(E)}$$

$$Kappa = KappaLoc * KappaHis$$

P(A) – fraction of agreement,
P(E) – expected agreement based on random location subject to the observed distribution,
P(max) – maximal similarity that can be found based upon the total number of cells taken in by each category.

Kappa results can range between <-1, +1>. A value of (+1) means total agreement (two maps are identical), the value of (-1) indicates that two maps are completely distinct and a result of 0 is statistically expected when randomly relocating all cells in the maps (Hagen, 2002).

It is worth to remember that the *Cell – by – cell* overlap and Kappa statistics should be restricted to cartometric source data (or to an assumption that historical maps truly project reality). Unfortunately, due to various geometric and cartometric distortions or inaccuracies (that can be only partly eliminated in rectification phase, Angold, 1995, Dragecevic et al., 2001, Dunajski & Sieczka, 2008), as well as due to possible dislocations occurring during vectorisation process, the analysis of data obtained from archival maps face many limitations. The errors, mentioned above, propagate and cause an overestimation of changes in quantitative landscape pattern analysis, as well as have a significant impact on the results of landscape modelling.

For the well recognized, small research areas such distortions can be visually corrected by so called *'backward editing'* vectorisation (Privat, 1996, Bender et al., 2005, Kienast et al., 1991, Neubert & Walz, 2002, 2005). In this process, the first vector layer is created for the latest (and assumingly most accurate) map and successive layers are produced working backwards in time to the earlier temporal layers by shifting the borders of only those polygons which changed in time. The approach is manual, quite laborious and to some extent subjective.

In order to semi-automatically reduce the error propagation when comparing archival topographic maps, the potential of fuzzy set theory (Zadeh, 1965) can be employed. According to the fuzzy set theory, a set can contain elements with only a partial degree of membership, thus variables can be expressed in a degree between 0 (completely false) and 1 (completely true):

$$A = \{(x, \mu_A(x)); x \in X\}, \text{ where: } \mu_A: X \rightarrow [0,1],$$

where:
A – fuzzy set,
X – a space of objects
x – element belonging to the space X,
μ_A – membership function.

There are the following possibilities:
$\mu_A(x) = 1$ $(x \in A)$,
$\mu_A(x) = 0$ $(x \notin A)$,
$0 < \mu_A(x) < 1$.

This approach allows to describe uncertain or imprecisely defined objects and processes (Longley, 2006) and, as they are common in the natural environment (e.g. soil division borders, ecotones, etc.), the use of fuzzy logic is of a growing interest among geographers (Syrbe, 1996, Steinhardt, 1998, Ołdak, 2001).

The use of fuzzy logic for map comparison is a relatively new approach (Metternicht, 1999; Winter, 2000; Pontius, 2000; Pontius and Schneider, 2001; Power et al., 2001; Hagen, 2003; Hagen-Zanker, 2006; Visser, 2004; Tang, 2009). An interesting algorithm for the use of fuzzy logic for raster map comparisons was developed by Hagen (2003). The algorithm accounts not only for fuzziness of categories but also for fuzziness of location (which means that fuzzy representation of a cell can be partly defined by neighbouring cells). The fuzziness of location is described by a membership vector and depends on the following factors: the cell itself, cells in its neighbourhood and the parameters of the membership function (the default is a function with exponential decay, halving distance of 2 and radius of neighbourhood of 4 cells). The similarity of two maps is assessed by pairwise comparison of the membership vectors assigned to the cells. This results in a third map indicating for each cell the level of similarity between 0 (totally different) and 1 (identical).

2. AIM OF THE STUDY

The presented study is aimed at verification of the fuzzy logic potential for quantitative land cover change analysis basing on historical topographic maps.

3. RESEARCH AREA

The research area is a part of Ponidzie Pińczowskie and consists of 400 km^2 (N –300 000 m, S – 280 000 m, W – 598 000 m and E – 618 000 m, along the PUWG 1992 gridlines). Ponidzie Pińczowskie is situated at the meeting point of the following mesoregions: Jedrzejowski Plateau, Wodzisławski Hummock, Nida Valley, Solecka Basin, Pińczowski Hummock and Połaniecka Basin (Kondracki, 2001). According to the administrative division of Poland, the research area is a part of Świętokrzyskie Voivodeship and belongs mainly to the Pińczowski District. The area distinguishes itself with a mosaic land cover and traditional rural character.

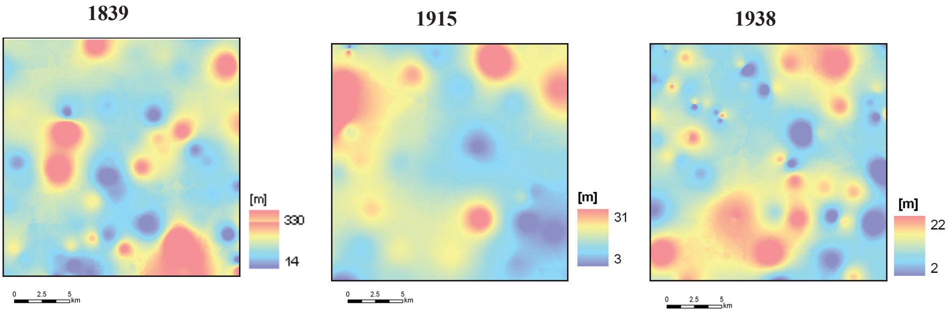
4. METHODS

4.1. Source data

Archival and contemporary topographic maps served as a source of information on land cover for particular moments in time. The interpretation of the land cover changes was based on the following maps: 1839 (TMKP – Topographic Map of the Kingdom of Poland, 1:126 000), 1915 (KWR – Karte des Westlichen Russlands, 1:100 000), 1938 (WIG – Tactical map of Poland, 1:100 000), 1974 (MTM – Military topographic map, 1:50 000), 2000 (TM – Topographic map 1:50 000, Head Office of Geodesy and Cartography).

The cartographic materials underwent rectification and registration in the 1992 Coordinate System. Contemporary topographic maps at a scale of 1:50 000, published by the Head Office of Geodesy and Cartography, were used as the reference layers. The polynomial transformation of the second- and third-order was applied. The process involved identification of Ground Control Points (GCP) series: *TMKP* – 110 GCP, *KWR* – 50 GCP, *WIG* – 114 GCP, *MTM* – 34 GCP. The accuracy of transformation was assessed by the value of the *Root Mean Square Error* (RMS_{TMKP} =170 m, RMS_{KWR} =15 m, RMS_{WIG} = 12 m, $RMS_{MTM} < 5$ m). The RMS obtained for the Topographic Map of the Kingom of Poland was high however, as European traditional landscapes developed a maximal diversity in the pre-industrial phase (Antrop, 1997), it was important not to reject this layer. For resampling the *Nearest neighbour* assignment was applied. The spatial distribution of residual error was illustrated using *Inverse Distance Weighting* interpolation (Fig. 1).

Thus prepared layers were manually vectorised and classified into three main land cover types: "forests", "grasslands", "others". The layers were then harmonised with respect to the minimum mapping unit (the smallest polygon vectorised from the oldest maps –TMKP and KWR – was 1ha). Finally, the data underwent conversion to raster format, with the resolution of 20 m.



Independent colour scales

Fig. 1. Residual error spatial distribution

4.3. A process of landscape pattern change detection

The *Fuzzy set approach,* as described by Hagen (2003), was applied. It was also referred to the results of pilot study (conducted for the fragments of Nidziańska Basin and South Pomeranian Lake District macroregions) related to the use of fuzzy logic elements when comparing maps representing two moments in time (Giętkowski & Zachwatowicz, 2010). The analysis was performed in Map Comparison Kit Software (Visser & Nijs, 2006) and ArcGIS 9.1 with *Spatial Analyst* tool.

The maps were compared in pairs, chronologically (1839 with 1915, 1915 with 1938, 1938 with 1974, 1974 with 2000) staring with the years 1974 and 2000 (the layer from 2000 was treated as the reference). The resulting map indicated the level of probability (in a range from 0 to 1) to which the particular cells did not change the category of land cover. The cells representing a high value of probability were attributed with: „false change", while the low values were considered to be „true changes". In order to decide on an adequately high level of probability, the histogram of the resulting map values was employed.

The next step was the reduction of the 'false' land cover changes. Using a simple map algebra in GIS 'false changes' were incorporated into adequate stable categories (forests, meadows or others) on the map of 1974 (a map from 2000 was used as a reference layer, thus could not be a subject of correction). Similarly, the layers of 1938 and 1974 were compared – in this case the layer from 1974, corrected in the previous step, was used as reference. According to the pair of 1915 and 1938, the 1938 layer corrected in the latest step acted as reference, while in the last phase the corrected layer of 1915 was used as reference.

In order to validate the results, the pairs of maps before correction and after correction were compared with the *Cell-by-cell* overlap. *Kappa* statistics (*Kappa, Kappa histo, Kappa location*) were calculated for every pair of maps.

By the comparison of *Kappa* values before and after correction, the effectiveness of the procedure was assessed. The increase of the Kappa values indicates that the similarity between maps has increased and thus the procedure has been successful.

5. RESULTS

By linking fuzzy logic, simple map algebra and *Kappa* statistics the uncertainty stemming from dissimilar quality of the archival maps was reduced, which made a distinction between 'true' and 'false' land cover changes possible (fig. 2a i 2b, fig. 3a i 3b, fig. 4a i 4b, fig. 5a i 5b). As a result, five corrected layers (1839, 1915, 1938, 1974, 2000) and four transformation matrixes (1839-1915, 1915-1938, 1938-1974, 1974-2000) were extracted.

Table 1. *Kappa* values 'before' and 'after' the correction of input historical source layers, for subsequent periods of time

	1839-1915		**1915-1938**		**1938-1974**		**1974-2000**	
	before	**after**	**before**	**after**	**before**	**after**	**before**	**after**
Kappa	0.62	0.66	0.78	0.82	0.84	0.87	0.89	0.91
Kappa location	0.68	0.72	0.86	0.90	0.89	0.92	0.95	0.97
Kappa histo	0.92	0.92	0.91	0.91	0.94	0.95	0.94	0.94

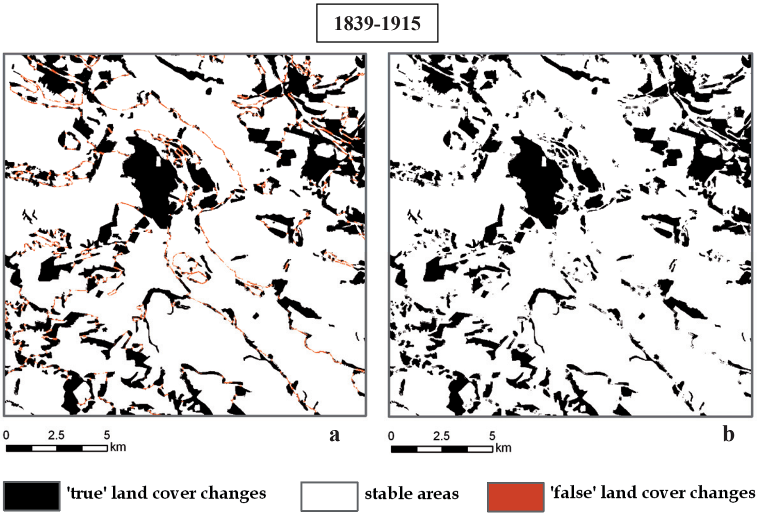


Fig. 2. Land cover changes between 1839 and 1915, a – before correction, b – after correction

The highest amount of ‘false’ land cover changes appeared in the periods of 1839-1915 and 1915-1938. They were detected at the edges of forest patches, as well as in the areas where arable fields neighbour the river valley and formed long and narrow pixel groups.

The overall similarity of maps increased (Table 1). The significant increase in the values of *Kappa location* indicates, that particularly spatial distribution of the different categories over the maps became more similar (spatial dislocations were reduced).

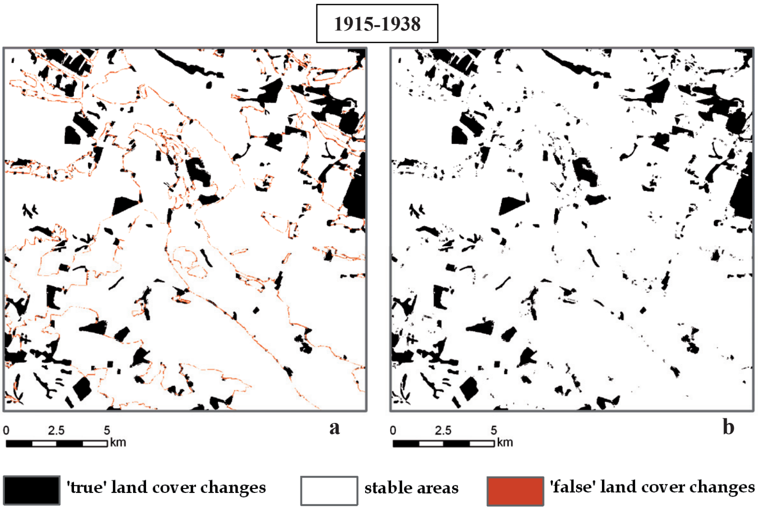


Fig. 3. Land cover changes between 1915 and 1938, a – before correction, b – after correction

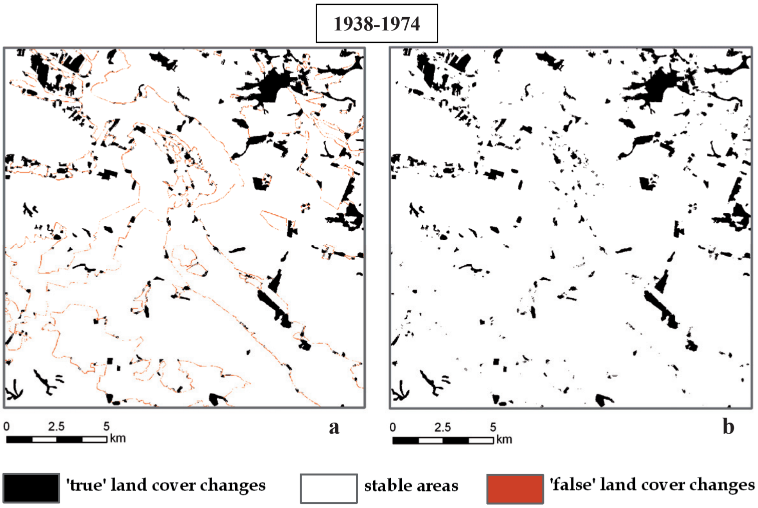


Fig 4. Land cover changes between 1938 and 1974, a – before correction, b – after correction

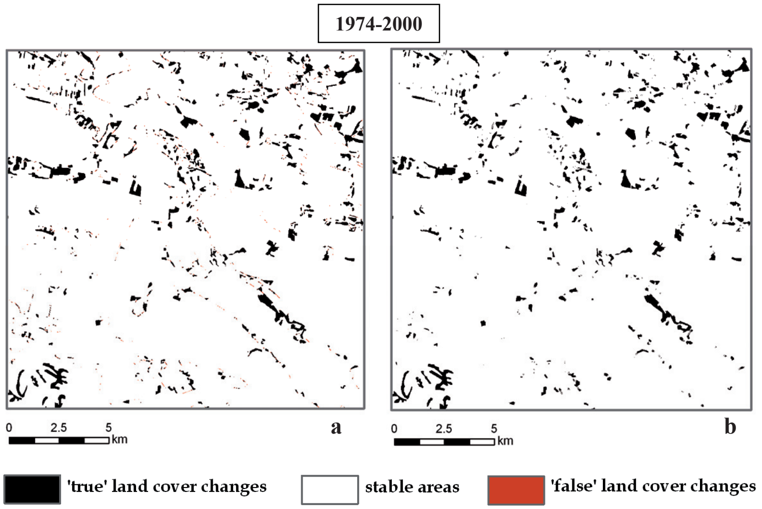


Fig. 5. Land cover changes between 1974 and 2000, a – before correction, b – after correction

6. CONCLUSIONS

Old topographic maps serve as an invaluable source of information on historical landscape pattern dynamics. Nevertheless, archival data need some transformation before they are ready to use in quantitative analysis.

The method presented in this paper allows to reduce the uncertainty stemming from dissimilar quality of the archival maps and to mitigate error propagation when comparing topographic maps. The corrected maps of land cover changes can be used for subsequent transformation matrix analysis in order to investigate the quantitative land use transformations in different periods of time or in predictive landscape pattern modelling. The procedure is automated, repeatable and predictable for a given input.

Still, there are issues that need clarification and further research. First of all, the relations in between the raster resolution, rectification error and parameters of the membership function should be defined. In the current study, the default parameters of the membership function were used, however it is probable that they could be better adjusted and optimised.

Secondly, the question has arisen: how to actualise the transformation matrix after the detection of ‘false’ changes in land cover? Here, an approach which can be called ‘retrospective-cascade actualisation’ was proposed. It refers to the ‘backward editing’ method. The process begins with the most recent map, treated as a reference, and proceeds backwards to the earlier temporal layers (always using the layer corrected in a previous step as a reference) The approach should be tested for different areas and map series.

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