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ANALYSIS AND REPRESENTATION OF UNCERTAINTY IN DIGITAL SOIL MAPS IN THE ŻYRZYN AREA (SE POLAND)

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Introduction

Soil maps fulfill different needs in the society and are used for multiple purposes. Concerning soil maps, McBRATNEY [1992] writes, that soil scientists have the „duty [...] to understand the soil and to be the providers and purveyors of accurate and precise information concerning it.".

The paradigm of individually different, crisp and mutually exclusive soil types in the landscape was challenged as early as in the beginning of the 20th century by the theoretical concept of continuous soil variation and gradual changes [BURROUGH et al. 1994]. Depicting variability of soils is done to increase certainty about the spatial arrangement of soils and efficiency in the use of resources in agricultural production or research. In the last two decades many authors have dealt with variability of soil properties on different scales and present tools for their study and representation [BURROUGH et al. 1994; DE GRUIJTER et al. 1997; BRAGATO 2004]. To model this paradigm geostatistics and fuzzy sets were studied intensively and proved to be useful since the early 1990s [BURROUGH et al. 1997; DE GRUIJTER et al. 1997; HANNEMANN 2003]. For an introduction into geostatistics and fuzzy set theory see e.g. WEBSTER, OLIVER [1990], and LARK [2001] and LARK, BOLAM [1997], respectively. The application of knowledge-based methods to process different input data sources, which was found useful in dealing with remote sensing data [SRINIVASAN, RICHARDS 1993], has not found yet its way into generation of the soil maps.

Increasing computing power and more sophisticated geographic information systems (GIS) made possible the processing of different data layers in increasingly larger scales. Only a few studies deal with the problem of explicitly uncertain data sources for the creation of soil maps and the resulting information content in these multi source classification results [MAYS et al. 1997; BISHOP et al. 2001]. Although Bayesian theory of conditional probabilities seems to be appropriate to model uncertainty of different data sources, in most cases enough data are not available to determine the specific probability distributions needed [MAYS et al. 1997].

The Transferable Belief Model (TBM) [SMETS, KENNES 1994] is an interpretation of the Dempster-Shafer-Theory of evidential reasoning [TSO, MATHER

2001]. It is similar to the concept of the Bayesian approach, although without the probabilistic assumptions. The TBM consists of two parts: the first step consists of assigning 'masses of belief' (*mob*) for a single hypothesis or sets of hypotheses of the frame of discernement to each data source, and a reliability weighting is accomplished for every data source. The *mob* and reliability are values within the interval (0.1). The concept of reliability is crucial to Dempster-Shafer theory and TBM, as it allows the operator to discount the *mob* according to the (real or assumed) uncertainty of the respective source of evidence (SOE). The second step combines the *mob* of different data sources by computing the orthogonal sums of all elements. By this, the originally assigned *mob* for hypotheses according to one SOE are rearranged, transferred, according to the *mob* of other SOE. See SMETS, KENNES [1994] and TSO, MATHER [2001 p. 281] for a more detailed introduction into the theory and examples.

For the concept of 'risk' requires probabilistic assumptions, SMETS, KENNES [1994] divide the TBM into two parts, a 'credal' and a 'pignistic' levels. The credal level deals with *mob* mathematically only, without making any assumptions about probabilities, but transfering and rearranging *mob* only. To support decision making and meet the requirements of 'risk' as a theoretical concept, the authors introduce a so called 'pignistic transformation', which represents subjective and case specific risk functions, and transforms the final masses of belief for single or multiple hypotheses into probabilities. Only on the pignistic level decisions are made.

This paper is divided into two stages: In a first stage, the aspects of general map unit purity (attribute uncertainty) and spatial imprecisions (spatial uncertainty) ars analysed for the study area. The second stage shows a GIS based application of the transferable belief model (TBM) to illustrate the methods potential for the improvement of digital soil maps. It deals with the integration and representation of the previously derived aspects of attribute and spatial uncertainty and the further improvement of soil maps by using classified remote sensing data.

Material and methods

The study region of Żyrzyn is situated in the south eastern part of Poland, 10 km east of Puławy and the Vistula river, 10 km south of the Wieprz river and 45 km north-west of Lublin. Agriculture is the predominant landuse in the area which developed from mainly sandy and sandy-loamy deposits originating from older stages of the Saalean ice age. The relief of the landscape is slightly undulating. According to Polish soil systematics predominating soil types in the study area are: „podzolic and pseudopodzolic soils" (A), „typical brown earths" (Bw), „black earths" (D), „black earths developed from deluvial" (Dd), and „degraded black earths" (Dz). No other soil types occured on the specific field under investigation (10 ha), according to soil map information at a scale 1:5 000. Other soil types in the area with only minor spatial extent are muddy „peat soils" (E), „gley soils" (G), and „peat and mucky peat soils" (T).

Digital soil maps were available in vector format at three different scales, 1:100 000, 1:25 000 and 1:5 000. To estimate the purities of single soil type mapping units at smaller scales, the polygons of the respective map and the map of next larger scale were intersected. Spatially weighted statistics for mapping units on the map at larger scale was calculated for each single mapping unit at the smaller scale. These values served as estimates for the purity of mapping units.

To assess the uncertainty of spatial information, records from the original georeferencing process of analog maps to the respective geographic reference systems would have been needed. No such information was available for the maps used. However, maps of the same scale were georeferenced to topographic maps with an residual mean square error (RMS) of 14 m for a region in western Poland. It was assumed that the RMS for the maps of this study will fall in the same magnitude.

Integration of attribute and spatial uncertainty was accomplished for a map at a scale of 1:5 000, using the TBM. The map unit purities were interpreted as general data source reliabililty. A constant value of 85% for the whole map was assumed as purity of polygon information. The RMS was interpreted as spatial data imprecision. As all calculations were performed on 5 m raster cell dimensions, the assumed RMS was increased to 15 m for lasier computations. Distances from vector polygon boundaries were transformed into continuous membership values for the respective soil type with a trapezoidal fuzzy set membership function and scaled to the interval (0.1). To obtain a composite soil type map with integrated information about uncertainty, the combination of overlapping soil type input layers was accomplished using the TBM with fuzzified polygon border distances as masses of belief and a reliability of 0.85 for polygon information. The result will be referred to as map_0 and later, for subsequent combination with the TBM, as source of evidence „soil map" ($SOE_{soilmap}$).

A colour aerial photograph taken on the 17.5.1997, showing bare soil mainly, served as a remote sensing information and additional SOE. To enhance the contrast within the image, reflection intensities of the image in red-green-blue colour space (RGB) were transformed to the hue-saturation-lightness colour space (HSL) and rescaled with a linear stretch and saturation of 1% of values at each end of the scale, filtered with a moving median filter of 5 x 5 pixel dimensions with three repetitions, and then transformed back to RGB colour space. The image was thinned to a resolution of 5 m pixel size. To secure an image segmentation procedure mostly unbiased by the human operator and applicable on large data sets also, fuzzy *k*-means clustering algorithm was applied using the freeware FuzMe [MINASNY, MCBRATNEY 2000], with the fuzzy exponent set to 1.5 and using the euclidean distance measure. Clustering was accomplished for 2 to 9 classes and the normalized clustering entropy (NCE) served as decision criterion for the optimal number of classes.

In order to perform the combination of data sources with the TBM, *mob* for each soil type had to be assigned to each cluster of air photo reflection intensity. Theoretical assumption about the expected general reflection properties of different soil types in the study area were drawn from the literature, and refined and adopted to Polish conditions in discussions with Polish soil scientists. An aera of 52 ha in the vicinity of study field served for testing these general assumptions on a quantitative level. *Mob* concerning the respective soil types were assigned to each of the clusters of remote sensing data. The result will be referred to as source of evidence, coming from the air photo ($SOE_{airphoto}$).

The $SOE_{airphoto}$ was combined with $SOE_{soilmap}$ using the TBM. Two cases of data source reliabilities were studied. In the first case, equal reliabilities of 0.85

were assigned to both SOE. In the second case, reliability for $SOE_{soilmap}$ was kept at 0.85, but $SOE_{airphoto}$ was considered more reliable, and therefore reliability was increased to 0.95.

Results and discussion

Table 1 shows the results for analysis of polygon purities of two maps at scales of 1:25 000 and 1:5 000. Apart from mapping unit D, all units with large spatial extent show individual purities of 75–95%. While there was no official document describing the purity for Polish soil maps at large scales, this analysis shows, that these maps have attribute purities near to or higher than the threshold of 85%, what, for example, is requested by the US Soil Survey Manual [BRUBAKER, HALLMARK 1991]. These authors report that analyses of maps often showed much smaller purities, sometimes in the magnitude of 50% only. Similar magnitudes of purities were found for the comparision of the soil maps at a scale of 1:100 000 with 1:25 000 for the study region.

Table 1; Tabela 1

Fractions of soil type mapping units at a scale of 1:5 000 within mapping units at a scale of 1:25 000 for the Żyrzyn area (analysed area: 1 862ha; columns sum to 100%; percentage of soil types within the 1:25 000 map are given in the column captions)

Udział typologicznych jednostek glebowych na mapie w skali 1:5 000 w obrębie jednostek glebowych mapy w skali 1:25 000 na obszarze Żyrzyna (analizowanych obszar 1 862 ha; wartości w kolumnach sumują się do 100%; udział procentowy typów glebowych na mapaie w skali 1:25 000 został podany w podpisie kolumn

1:25 000 1:5 000	A 48.2%	Bw 17.1%	D 8.0%	Dd 0.8%	Dz 10.9%	E 0.1%	G 10.6%	T 4.3%
empty; pusty	0.13	0.23	0.28	0.97	0.12	–	–	–
A	89.18	16.67	15.73	0.10	10.17	18.75	1.08	–
Bw	5.10	74.79	7.96	29.42	4.44	11.30	0.80	–
D	2.15	2.24	58.03	11.13	3.20	–	2.96	–
Dd	–	0.68	0.94	55.36	–	–	–	–
Dz	3.29	4.87	13.69	1.10	81.37	–	3.81	3.95
E	–	0.08	–	–	0.21	69.95	–	–
G	0.15	0.44	3.37	1.92	0.49	–	91.34	1.00
T	–	–	–	–	–	–	–	95.05

Explanations see „Material and methods"; Objaśnienia patrz „Material and methods"

The RMS error as a measure for the spatial uncertainty of soil information is much higher than the initially expected error and values normally reported for georeferencing of analog data sources. As a standard, the RMS should fall within the range of one to two input image units only [EASTMAN 1999]. In this study, this would have meant a RMS of maximum 2 m. A possible explanation for the difference to the RMS found lies in the specific circumstances of soil mapping in Poland after 1950. Because of military security reasons, all topographic maps available for public and scientific tasks were manualy falsified to an unknown extent. The soil mapping procedure in the 1960 had to use these falsified spatial information to create their maps. Therefore unregular distortions within one map sheet are a common feature in Poland when soil maps are compared with correct topographic information [OSTASZEWSKA 2005; STUCZYŃSKI 2005].

Figure 1 shows the original soil map, the new map with the introduced concept of uncertainty and the values of maximum belief for this map. The new map is named map_0 to stress the point, that this is the initial stage of map improvement. The original data source reports one soil type per pixel only, and has no information about uncertainty, neither concerning attribute information nor spatial aspects. The concept of data representation of this map assumes 'certainty' for the soil type at any location. However, specific information about uncertainty or completeness of the data source might be conveyed in a metadata file.

Alternatively, map_0 shows single soil types or sets of soil types, which have the highest amount of belief after combination within the TBM. There are alternative strategies for the decision which hypothesis to assume, as from the TBM beliefs, plausibilities and the intervals between plausibility and belief could be calculated for every location as well and subsequently used as decision criterion [TSO, MATHER 2001, p. 285]. However, the maximum belief is closest to the traditional way for the construction of soil maps. Near to polygon borders, maximum belief is low and furthermore not assigned to a single soil type only, but in many cases to a set consisting of the adjacent soil type hypotheses. This represents the decision uncertainty at or near to polygon borders, where one does not know exactly whether to expect one soil or the other.

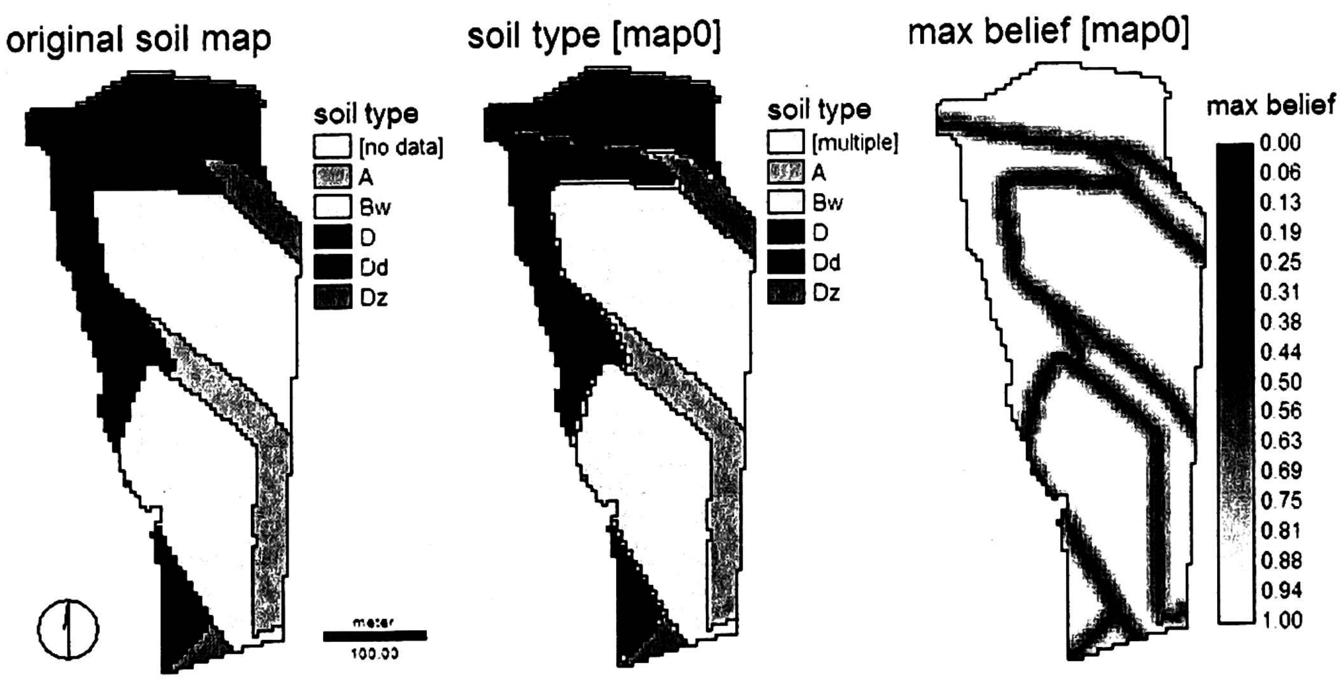


Fig. 1. Map of soil types of the study area without information concerning uncertainty (left), with integrated attribute and spatial uncertainty data (map_0, centre) and values for maximum belief for the respective hypothesis of map_0 (right)

Fig. 1. Mapa typów glebowych analizowanego obszaru bez informacji na temat niepewności (mapa lewa), ze zintegrowaną informacją na temat niepewności dotyczącej występowania i przestrzennego rozmieszczenia typów gleb (środkowa mapa0) oraz maksymalnej wartości wiary dla odnośnych hipotez dla mapy0 (mpa prawa)

Although in this data set the spatial transition area is 3 pixels wide, in most cases only the pixel directly overlaid by the polygon border vector is affected by this type of non-singleton hypothesis with maximum belief. This is a result of the specific numerical values of the two aspects of uncertainty, the fuzzified distance value and the data source reliability. As the reliability value decreases, pixels with larger distances to the polygon border tend to be assigned with sets of hypotheses rather than singletons (data not shown). The map of maximum belief values shows that 1.00 as maximum belief for attribute information occurs in the central part of polygons. This is similar to the assumption inherent in the original map. However, belief values decrease to 0.32 at the border regions. Assuming a general SOE reliability of 0.85, these values reduce to 0.85 and 0.27, respectively. This procedure makes possible the separation of general reliability of the attributes and spatially defined uncertainties. Map_0 is considered as $SOE_{soilmap}$ for the following stages of processing with the TBM.

Table 2; Tabela 2

Statistics for reflection intensities of soil types in the training area (left) and *mob* assigned to fuzzy clusters of air photo reflection intensity for hypotheses about soil types (right)

Wartości statystyczne intensywności odbicia światła dla typów gleb na obszarze treningowym (lewa część) oraz wartości *mob* przypisanych do grup rozmytych intensywności odbicia światła na zdjęciu lotniczym dla hipotezy dotyczącej typów gleb (prawa część)

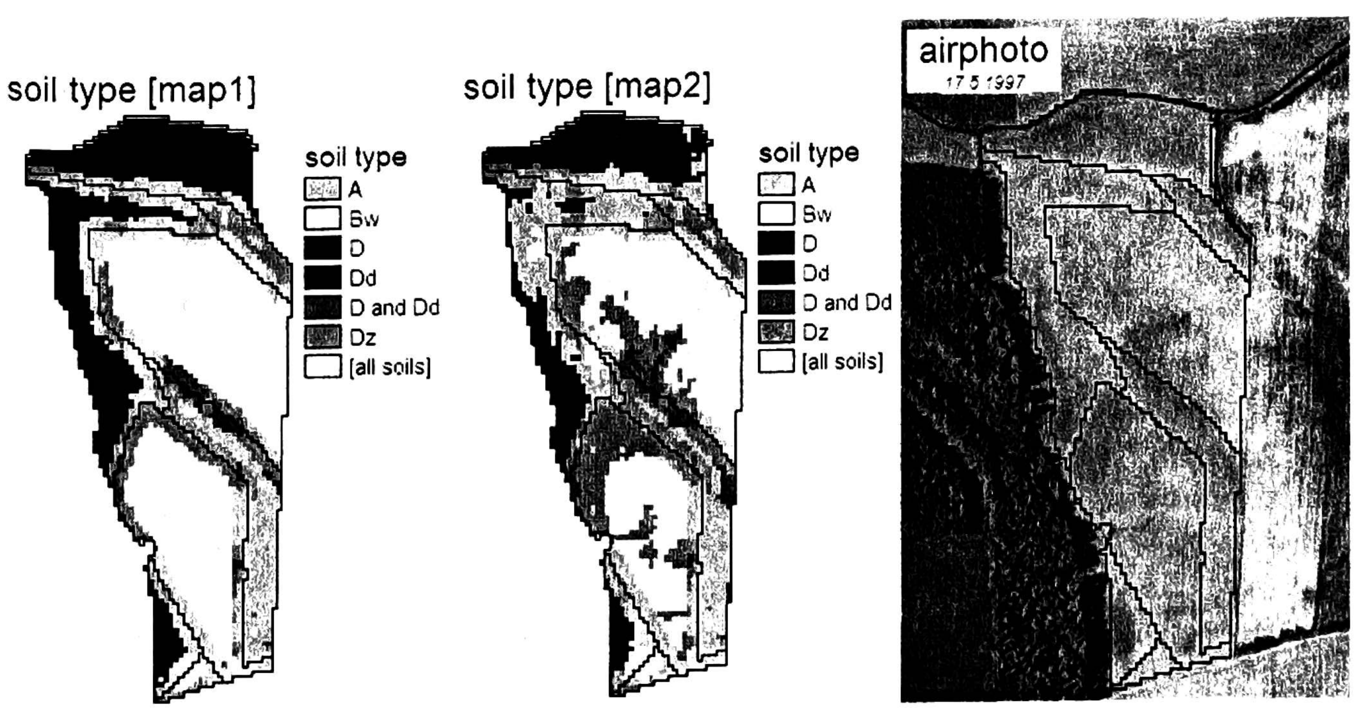
Soil type (ID) Typ gleby (ID)	Statistics of reflection intensity in training area Wartości statystyczne intensywności odbicia światła na obszarze treningowym				Masses of belief (*mob*) Siła wiary (*mob*) — name of fuzzy *c*–means cluster ($c = 4$) nazwy grup rozmytych ($c = 4$)			
	n	min	mean średnia	max	very low bardzo niska	low niska	medium średnia	high wysoka
A (1)	84	111	165	203	–	–	0.70	0.20
Bw (2)	37	145	173	197	–	–	0.20	0.80
D (4)	71	96	136	172	0.90	0.30	–	–
Dd (8)	4	158	172	185	0.90	0.30	–	–
Dz (16)	35	113	152	194	0.10	0.70	0.10	–

To further improve $SOE_{soilmap}$ regarding the spatial arrangement of soil types, a classified air photo was included ($SOE_{airphoto}$). The normalised entropy criterion of the fuzzy *c*-means clustering of the air photo data had its minimum for $c = 4$ classes. The derived clusters can be interpreted as visual reflection intensities, and were subsequently named as 'very low', 'low', 'high' and 'very high'. The lowest reflection intensity for soil types in the training area was found for 'black earths', followed by 'degraded black earth', 'pseudopodsolic soils' and 'brown earth' (Tab. 2, left columns). This is in accordance with general knowledge about reflectance properties of soils in Poland and elsewhere [TURSKI, FLIS-BUJAK 1975; BAUMGARDNER et al. 1985]. The number of pixels for soil type 'Dd' in the training area was very small. Visual comparison led to the conclusion, that these pixels were obviously not representative for this soil type as well, and therefore the results were not used for further assignment of the *mob*. Hypotheses and *mob* were assigned to the fuzzy clusters of the study field using soil type specific mean, minimum and maximum reflection intensities in the training area (Tab. 2, right columns). The strength of histogram overlap in the reflection intensities for different soil types was used to subjectively assign values of decreasing *mob* for non-typical cluster-hypothesis combinations. The soil types 'black earth' and 'deluvial black earth' represent similar soils but from different origin of the parent material. Therefore it was considered unlikely to distinguish between them on the basis of reflection intensities only. For this reason, 'D' and 'Dd' are treated as a set of hypotheses and their respective *mob* can not be defined more precisely.

Figure 2 shows the two new soil maps as a result of the $SOE_{soilmap}$ combination with $SOE_{airphoto}$ for two reliability scenarios (top left & centre) and the air photo (top right) used in the analysis. As well, the resulting maximum belief values for the respective soil maps and their ratio are displayed (bottom left, centre & right). Map_1 is the result of assuming equal reliabilities of 0.85 for both sources of evidence, while for map_2 the reliability for the $SOE_{airphoto}$ was increased to 0.95. For better comparison, the border lines of the soil types of the original 1:5 000 soil map are displayed also.

It is obvious from the air photo already, that the reflection intensities of the bare soil surface show spatial structures that generally correspond with the patterns of soil map. However, especially the dark area in central part of the field, lying in the Bw-polygon (see Fig. 1, left), suggest, that soil types might be arranged differently, for Bw soils tend to have relatively high reflection intensities compared to other soils under the same conditions.

Field examinations in September 2004 showed black earth soils (D) with more than 50 cm of dark humic horizon from siltloam and thistle plant communities to be at these locations, only a few meters away from brown earths developed from coarse sand without any plant growth. These dark structures are therefore a combined effect of higher organic carbon content and loamy soil texture. The distribution of soil types was obviously linked to terrain features, as the black earths were found in a local depression, surrounded by sandy material.



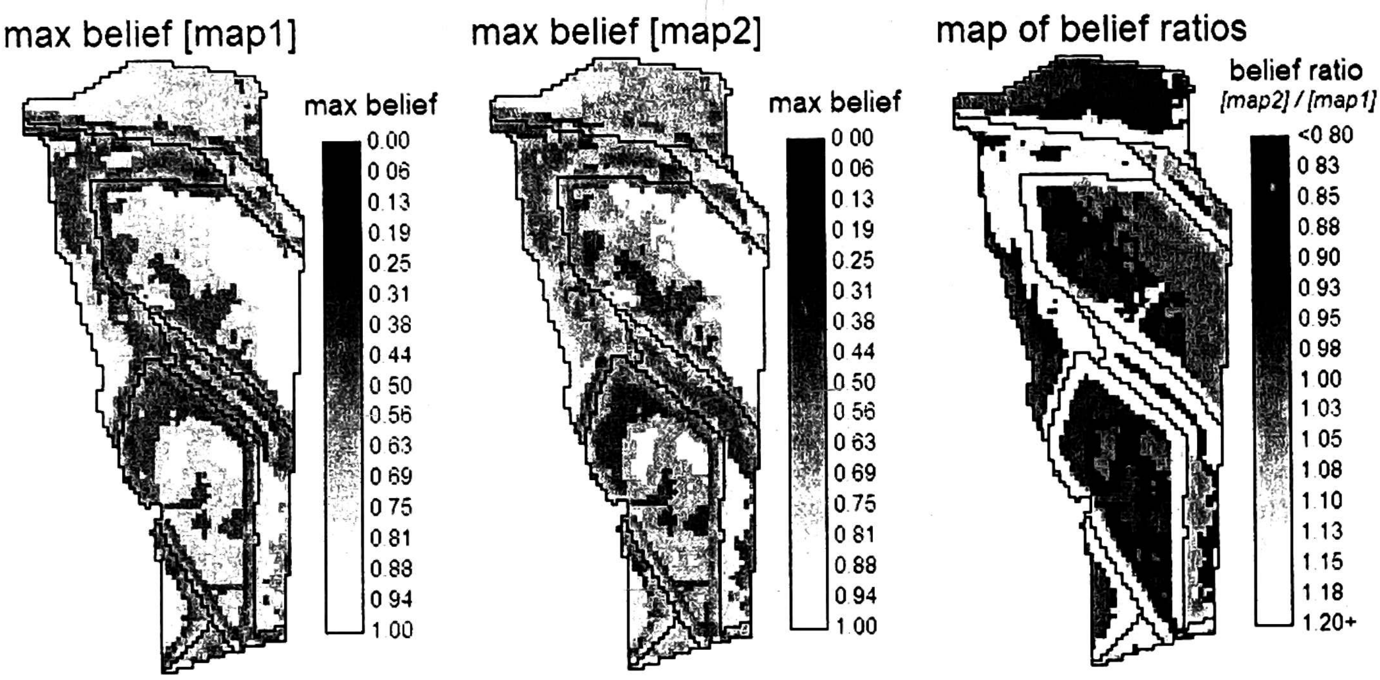


Fig. 2. Maps of soil types and maximum belief values after TBM combination of $SOE_{soilmap}$ with $SOE_{airphoto}$ for the reliability scenarios 0.85/0.85 (map_1, top & bottom left) and 0.85/0.95 (map_2, top & bottom centre) for the respective SOE, the aerial photo of the study area used for classification (top right) and ratio map of maximum belief values ($maxBELmap_2/maxBELmap_1$, bottom right) (see text for details); the borders of the original soil map are displayed as vector line

Fig. 2. Mapa typów gleb i maksymalnych wartości wiary po procedurze TBM obejmującej $SOE_{soilmap}$ i $SOE_{airphoto}$ dla scenariuszy rzetelności 0,85/0,85 (mapa1, lewa strona góra i dół) oraz dla scenariuszy 0,85/0,95 (mapa2, środek góra i dół) dla odpowiednich SOE. Zdjęcie lotnicze badanego obszaru wykorzystane w celu klasyfikacji (prawa strona góra). Mapa ilorazów wartości maksymalnej wiary ($maxBELmap_2/maxBELmap_1$, prawa strona dół). Granice oryginalnej mapy glebowej zaznaczone są jako linia wektorowa

On map_1 the changes in hypotheses of soil types are located in the polygon border regions mainly. This is due to the reduced belief values in $SOE_{soilmap}$ at these locations. The 'D & Dd' hypothesis is introduced in the polygon border region in the central part. The additional *mob* from $SOE_{airphoto}$ induce changes by transfer of *mob* from original hypotheses to new hypotheses or sets of them. However, the spots in central area with low reflection intensities are not yet depicted in map_1. The reason for this lies in the equal reliability assumption. However, the TBM produces additional information concerning the uncertainty of combination result, the respective new masses of belief. It is obvious from Fig. 3 (left), that map_1 has a spatially varying degree of maximum belief in the central area, where the hypothesis for soil type is uniformly 'Bw'. For the dark areas in the aerial photo, the respective maximum beliefs are rather low for equal data source reliabilities (map_1). This means, that there is conflict between the hypotheses supported by the two SOE. This is reflected in the weights of conflict (WOC) as well (data not shown). In the case of different reliabilities for the two SOE, the spatial structures of resulting soil type map_2 (Fig. 2, top centre) and maximum belief values (Fig. 2, bottom centre) alter significantly. Map_2 depicts new spatial patterns of soil types and it looses the similarity with the original map (Fig. 1). Within the Bw-polygon in central part of the image, new soil type hypotheses occur, namely 'Dz' and 'D/Dd', reflecting the assumption, that the dark spots in aerial photo hypothetically may represent these soils rather than 'Bw', as is proposed by the original soil map. This was found to be correct by ground truthing. Simultaneously, the maximum beliefs increase for this specific region by ca. 20% (Fig. 2, bottom right). The bright areas near the former polygon borders on the ratio map illustrate, that the assumption of higher reliability of $SOE_{airphoto}$ leads to higher belief values in these areas for map_2 (ratio > 1.0). However, the maximum belief values for central areas of the polygons remain mainly unchanged by the different reliability assumptions of data sources.

It has to be emphasized, that this second part of study is mainly aimed at introducing and illustrating the *general procedure* of the TBM application for improvement of soil maps within GIS. The validity of the resulting map has to be assessed by ground truthing or other independent data sources. Further research is necessary also, to assess the general impact of specific reliability values for the sources of evidence, as proposed by SMETS [2000]. As well, the meaning of quantitative values of maximum beliefs and the weights of conflicts should be investigated further to gain the knowledge on possible thresholds of these criteria and connections to human reasoning and expert decisions. As well, the general reflection properties of soil surfaces and soil types in specific landscapes should be studied in more detail. Because aerial photography reports the data in visual spectrum there is a very close connection to human reasoning and expert decisions. Aerial photography of bare soils should be studied more intensively, to increase the interpretative power of this well established data source.

Conclusions

Information from Polish soil maps at various scales show spatial and attribute uncertainties that are due to the production of the maps. These uncertainty information should be integrated into spatial databases to support modelling and decision making. Analysis of maps at different scales of the Żyrzyn area in SE-Poland showed, that the attribute uncertainty is within normal limits. However, spatial uncertainty about the exact border lines is large and not deductable from the maps themselves, as the topographic base maps were intentionally distorted for security reasons.

The transferable belief model and remote sensing information can be used to assess the spatial imprecisions and remediate some of them However, the new information about uncertainty enables us to concentrate the financial and labour resources for updating soil maps on these regions were the highest conflicts between data sources appear.

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Key words: soil map, transferable belief model, GIS, uncertainty, remote sensing, efficiency

Summary

The transferable belief model (TBM) is used to combine the soil information from soil maps and remote sensing information from colour aerial photography in two steps, with respective assumptions about the uncertainty and reliability of data. At a first step, the soil type maps of different scales were analysed for mapping unit purity to derive a soil map with integrated uncertainty information (map_0). In the second step, belief values regarding soil type hypotheses were assigned to pixels derived from airphoto classification. The 'soil type – air photo class' combinations were determined according to results from tested area. This new map was combined with map_0 using TBM. Two scenarios for data reliability were studied. The resulting soil type map is depicting spatial variability visible on the airphoto, when data reliability was increased for remote sensing information. The additional values of maximum belief and weight of conflict from the TBM can be integrated into GIS as spatial uncertainty information.

ANALIZA I REPREZENTACJA NIEPEWNOŚCI CYFROWYCH MAP GLEBOWYCH OBSZARU ŻYRZYNA (POŁUDNIOWO-WSCHODNIA POLSKA)

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Słowa kluczowe: mapa glebowa, TBM, GIS, niepewność, tolerancja, skuteczność

Streszczenie

Wykorzystano transferable belief model (TBM) do łączenia informacji o cechach gleby pochodzących z map glebowych i zdjęć lotniczych w dwóch etapach, z uwzględnieniem pewności i niepewności danych. W pierwszym kroku, porównano mapy glebowe (różne skale) w celu określenia ich wspólnego mianownika dokładności („czystości") w wyniku czego powstała mapa „niepewności

informacji" (map_0). W drugim kroku wartości zaufania dotyczące hypotezy odnośnie typów glebowych zostały przypisane do pikseli otrzymanych na podstawie klasyfikacji zdjęć lotniczych. Kombinacje klas zdjęć lotniczych z typami gleb zostały określone na podstawie wyników z obszaru testowego. Nowa mapa została połączona z $mapą_0$ z wykorzystaniem TBM. Badano dwa scenariusze dotyczące pewności danych. Wynikowa mapa glebowa przedstawia zmienność przestrzenną, która jest widoczna na zdjęciach lotniczych, gdy pewność danych wzrosła po zastosowaniu informacji z teledetekcji. Dodatkowa ocena maksymalnego zaufania oraz współczynnik wagi konfliktu otrzymane metodą TBM mogą być włączone jako przestrzenna informacja o niepewności w GIS.

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