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APPLICATION OF OBJECT-ORIENTED ANALYSIS TO STUDY LANDSCAPE STRUCTURE

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INTRODUCTION

Structural and functional complexity of the environment makes up a significant barrier in elaborating an effective method of its integrated studies. The dilemma has been undertaken by landscape ecologists for many years. Amongst other concepts German, Russian and Polish landscape ecology has worked out a 'geocomplex' model. 'Geocomplex' is understood as an universal spatial unit, relatively confined and inherently integrated due to its intrinsic processes and interrelations between its components (Richling, 1982). Geocomplexes should be regarded as autonomic entities and as integral parts of superior units (Richling, Solon, 1996). They constitute a hierarchical system, starting with small homogeneous 'facja' at the lowest level, and ending with the whole epigeosphere (German, 1992). The hierarchical structure of the environment is understood by many as its immanent attribute, reflecting the nature of environmental system (Jelinski, Wu, 1996; Richling, Solon, 1996; Solon, 2000).

In Polish landscape ecology there are two ways of landscape perception and description: typological (emphasizing similarities) and regional (emphasizing individual distinctions) (Ostaszewska, 2002). Typological units are relatively homogeneous while regional ones are heterogeneous, i.e. they include structurally extrinsic components (Richling, 1993). For delineating small 'geocomplexes' ('facja', 'uroczysko', 'teren') mostly field mapping is being conducted (Richling, 1982). Larger geocomplexes are obtained either by merging typological units or by sequential divisions of large areas into regional units on a basis of discontinuities and spatial differences (Richling, 1993). The latter approach was used e.g. by Olędzki (1992) to establish a photomorphic regionalization of Poland based on Landsat satellite imagery.

As exemplified by the last example, remote sensing has contributed for several decades to new approaches in landscape ecology. At the same time new methodological dilemmas have been formulated as well. M. Pietrzak (2003) points out a few of them, like 'pixelisation' of the landscape (i.e. replacing basic landscape units with pixels) and overestimation of the role of vegetation or land cover in landscape structure studies (being relatively easily derived from satellite imagery). At the same time pixel-based classifications of digital aerial or satellite imagery have been criticised and suggestions have been put forward that it does not take into account the contextual information, fundamental in geographic analysis (Blaschke, Strobl, 2001; Huiping et al 2003).

The object-oriented analysis can be an alternative way of automatic processing of image data, free of the disadvantages of the pixel-based approach. Here, basic processing units are segments (homogeneous groups of pixels) which can be similar to those obtained via manual interpretation (Blaschke, Strobl, 2001) and may represent real world entities much better than pixels (Benz et al 2003). Additionally, the object-oriented analysis enables mixing different data in the process of delineating of spatial units. There are several recent examples showing that the approach can be very effective in the framework of landscape ecology (Blaschke, Strobl, 2001; Schieve et al 2001; Burnett, Blaschke, 2003; Drăgut, Blaschke, 2006).

This paper presents the results of a study carried out within the author's master thesis (Sukiennik, 2006). It attempted to combine traditional geoecological framework ('geocomplex' model) with modern technology (remote sensing, GIS) within landscape structure studies. The aim of the work was to implement an automatic division of the study area into a set of hierarchically ordered spatial units and to evaluate the potential of the object-oriented image analysis in this context.

For many years in Poland, the Department of Environmental Remote Sensing at the University of Warsaw has been a leading center for research of structure and regionalization of landscape using photointerpretation methods. Its major achievements include book publications by J.R. Olędzki, "Geographical preconditions for diversity in satellite imagery of Poland and its division into phototonal units " (1992) and "Geographical regions of Poland" (2007), as well as articles by A. Jakomulska concerning remote sensing of mountain regions. Also, A. Ciołkosz and M. Baranowski of GRID Warsaw, could claim significant accomplishments. The achievements of these institutes have not been included in the article by the author (note ed. J.P).

STUDY AREA AND MATERIALS

A 20x20 km sample located in the West Carpathians was selected as a case study area. It is located at the boundary of the Outer Carpathians (mesoregions: Gorce, Pogórze Orawsko-Jordanowskie and Beskid Wyspowy) and the Inner Carpathians (mesoregion of Kotlina Orawsko-Nowotarska) (Balon, et al 1995). Several geographical divisions and hierarchies of spatial units, obtained using traditional approaches, were proposed for the case study area. For example, Starkel (1972) distinguished here three main relief types: middle mountains (part of the Gorce Mountains), foothills (part of Pogórze Orawsko-Jordanowskie and Działy Gorczańskie), basins and valley floors (part of Kotlina Orawsko-Nowotarska).

For the analysis a Landsat ETM+ satellite image, path 187, row 26, acquired 20 August 2000 (GeoCover Technical Guide, 2006), and a digital elevation model were chosen. The satellite image has a spatial resolution of 30 m, its five spectral bands (TM1-TM5) were used in the analysis. The digital elevation model obtained within the PHARE programme (1995-1999) has a spatial resolution of 20 m and a vertical accuracy of 4-5 m (Preuss, Kurczyński, 2002; information provided by S. Podlasek, Wojewódzki Ośrodek Dokumentacji Geodezyjnej i Kartograficznej, Krakow).

OBJECT-ORIENTED IMAGE ANALYSIS

Object-oriented image analysis starts from a segmentation process, i.e. an automatic division of an image into coherent groups of pixels (segments, objects). One of the criteria used to segment an image is a degree of homogeneity within each particular object and heterogeneity among neighbouring objects (Baatz, Schäpe 2000). In practice, any type of geographically meaningful variables (e.g., slope, land use, aspect) can be declared for the procedure of image segmentation.

Furthermore, the object-oriented analysis can have a multi-scale character. It is possible to create interrelated object levels with segments of different sizes; each level being constructed using different variables and segmentation parameters. That allows building and testing various hierarchies of spatial units, enabling simultaneous studies at different scales (eCognition Professional User Guide 4, 2004). Additionally, multi-scale capabilities help to incorporate a specific processing logic for different regions: e.g. other for mountainous parts and others for plain areas (Benz et al., 2003).

Moreover, one can use more sophisticated tools within the segmentation procedure (e.g. fusion of selected objects), based on results obtained from previously performed segmentations and classifications. While the output of a simple segmentation are so-called 'object primitives', the subsequent tasks lead to meaningful 'objects of interest' (eCognition Professional User Guide 4, 2004). Those can be e.g.

structurally heterogeneous but spatially coherent object (regions). It means that pixels or sub-objects forming particular regional unit do not have to be spectrally similar, provided they have a specific meaning for a user (e.g., mountainous areas will be those which have not only high relative altitude and steep slopes but some gentle slopes and adjacent flat valley floors as well). Therefore, digital processing can be effectively enriched with the spatial context, regarding complex topological relations of objects, like adjacency or containment (small objects being a part of larger structures).

Segments are basic units used in the subsequent classification. An advantage of objects, contrary to pixels, is the availability to use several additional variables in the classification process, e.g. texture, shape, statistical parameters of image values (mean, min, standard deviation etc.), topological (e.g. spectral differences between neighbours) and hierarchical features (e.g. relations to sub- and super-objects). In this way an object-oriented classification may more accurately mirror the real-world entities (Benz et al., 2003).

WORKFLOW

For preprocessing Erdas Imagine 8.7 and ArcGIS 9.0 was used. Three derivatives of digital elevation model (aspect, slope, curvature) and one of satellite imagery (land use with three basic classes: forests, agriculture and others) were generated.

Fundamental processing was done in eCognition 4.0®. The segmentation procedure used in eCognition uses a fractal approach (FNEA – Fractal Net Evolution Approach) and can be explained as an iterative merging of smaller objects (started with one pixel objects) into bigger ones (Baatz, Schäpe, 2000).

Because of the data chosen for analysis the delimitation of highest rank units were based on relief types. The fundamental workflow consisted of repeated segmentations, classifications and fusions. Different criteria and parameters for those procedures were used (tab. 1, fig. 1).

In the first stage spatial units of different rank and their classification were obtained. First, a boundary between **valley and basin floors** and **middle mountain and foothills** relief types was set. **Valley and basin floors** relief type has not been used for further processing because of insufficient vertical accuracy of digital elevation model in this area. Next, main relief forms (hilltops, valley floors, slopes) within **middle mountain and foothills** relief type were distinguished. Finally, a delimittation and a classification of the smallest units, in the rank of **uroczysko**, were accomplished (3^{rd} rank units).

Tab. 1. Parameters and criteria of spatial units delimitation.

STAGE	CLASSES	SEGMENTA-TION LAYERS, (SP; SI)[1]	BASIC CLASSIFICATION'S CRITERIA	ADDITIONAL CLASSIFICATION'S CRITERIA	ADDITIO-NAL OPTIONS
1	relief of valley bottom relief of middle mountain and mountain	slope (35; 0.3)	*slope* < 3º *slope* > 3º	regrouping to the opposite class of these objects which are in 95% surrounded by the opposite class	fusion of the same class segments
2	valley bottoms hilltops slopes	slope, curvature (10; 0.1)	mean of *curvature* <0, Ratio[2] for *altitude* < 0.4 mean of *curvature* >0, Ratio[2] for *altitude* ≥ 0.49, mean of *slope* ≤ 6º (see German 1992), mean difference to neighbours of *slopes* ≤ -2.5 left segments	regrouping to 'hilltops' of these segments which are in 95% surrounded by hilltops	fusion of the same class segments
3	units in the rank of 'uroczy-sko'	slope, aspect, land use (10; 0.1)	15 classes which are a combination of three *land use* classes (forests, agriculture, others) and five *slope* classes with thresholds: 3º, 6º, 10º, 15º	-	-

Source: *compiled by the author.*

In the second stage units of the 2nd rank were distinguished. They included sets of **uroczysko** units situated within main relief forms (relative homogeneous parts of **valley floors, hilltops** and **slopes** with similar slope gradient value).

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[1]SP – scale parameter; SI – shape index.

[2]the ratio of layer is the layer mean value of an image object divided by the sum of all spectral layer mean values.

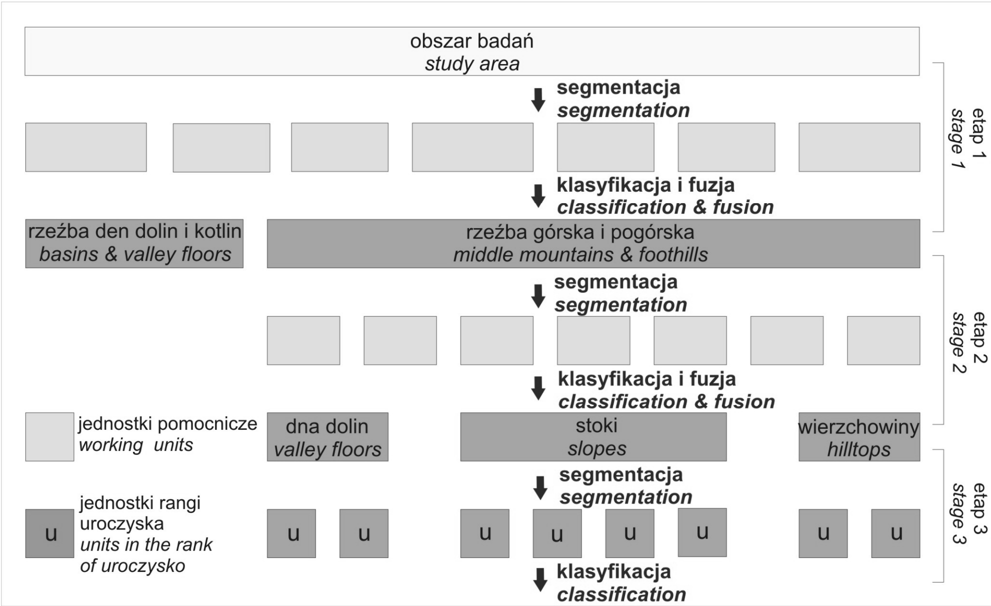

Fig. 1. Research workflow. ***Source:*** *compiled by the author.*

After that 2nd rank units were used to find a boundary between **middle mountain** and **foothills** relief types (delimitation of the 1st rank units). To achieve this, **hilltop** units were classified into middle mountains' hilltops and foothills' hilltops on a basis of the relative altitude, with a threshold value of 200 m, accepted after Starkel (1972). Technically, a custom feature in the software was defined, which compared mean altitude of two classes: valley floors and hilltops. Then, an analogous classification of the **slope** type was done. Middle mountains' slopes were defined as slopes with an slope gradient over 15º (preliminary visual evaluating of the slope gradient map) or those which were neighbours of middle mountains' hilltops; as middle mountains' slopes – all remaining segments of the slope type. Next, a parallel classification of **valley** units was made. In this case neighborhood relations with middle mountains' slopes units were used. Finally, a fusion of all mountain units was performed to complete the delineation of **middle mountain** relief region. The remaining objects have formed the **foothill** relief region. Those units: **middle mountains, foothills** and **valley and basin floors** are three large 1st rank units.

The third stage of the processing workflow consisted of the graphical, statistical and descriptive synthesis of information about the landscape structure of study area, done mainly on the basis of 2nd rank units. It took into account their membership with particular relief type (relation to 1st rank units) as well as individual morphological features and land use (defined by the percentage of specific 3rd rank sub-units).

RESULTS

An outcome of the analysis was a division of the study area into hierarchically arranged spatial units. It allowed a description of the study area environment over a range of scales. At the 3rd level 9856 spatial units (average size of 2.9 ha) were delimited and classified into 15 classes, using slope and land use variables. These units are analogous to traditional 'uroczysko' units (Kondracki, 1976), relatively homogeneous referring to slope gradient, aspect and basic types of land use.

The 2nd level division consist of 694 spatial units (average 46.8 ha), with higher intrinsic heterogeneity, grouped in 24 types (fig. 2), reflecting the structure of sub-units from the 3rd level. One can compare them with 'teren' or 'ekochora' in the traditional approach (Richling, 1993). They include sets of hilltop units, slope units with respective slope gradients (referring to quantitative domination of a particular type) and valley floor units. Each 2nd level unit present a coherent kind of energy and matter cycle and one type of mesoclimat (see Hess et al, 1975). They are also expected to have a relatively homogeneous lithology (under the assumption of high correlation between lithology and morphology).

The highest level (1st rank) consists of three large regional units: **middle mountains** (17 820 ha), **foothills** (12 480 ha) and **basins and valley floors** (5 200 ha) (fig. 1). Each 1st rank type contains a specific set of 2nd rank sub-units but may also include several atypical units, characteristic for other 1st rank types. Comparison with map of geomorphologic units (fig. 3) showed a general agreement of boundaries of the 1st rank units with traditionally delimited relief types. Only a gently sloped hilly region (slope gradient 4-5º) between Brama Sieniawska and Kotlina Orawsko-Nowotarska was included to **foothills** type, contrary to the proposal of Starkel. The likely reason of this difference is that in this work only morphologic criteria were taken into account. To receive a better convergence with the division of Starkel (1972) additional lithologic information should be incorporated into processing. In case of the **foothills** type where Starkel (1972) distinguished three geomorphologic meso-regions, it was not possible to detect significant regional boundaries. Probably the more exact demarcation within the **foothills** type could be possible if the analysis had been done for a larger study area, providing a wider spatial context and better possibilities to detect meaningful differences within the **foothills** type.

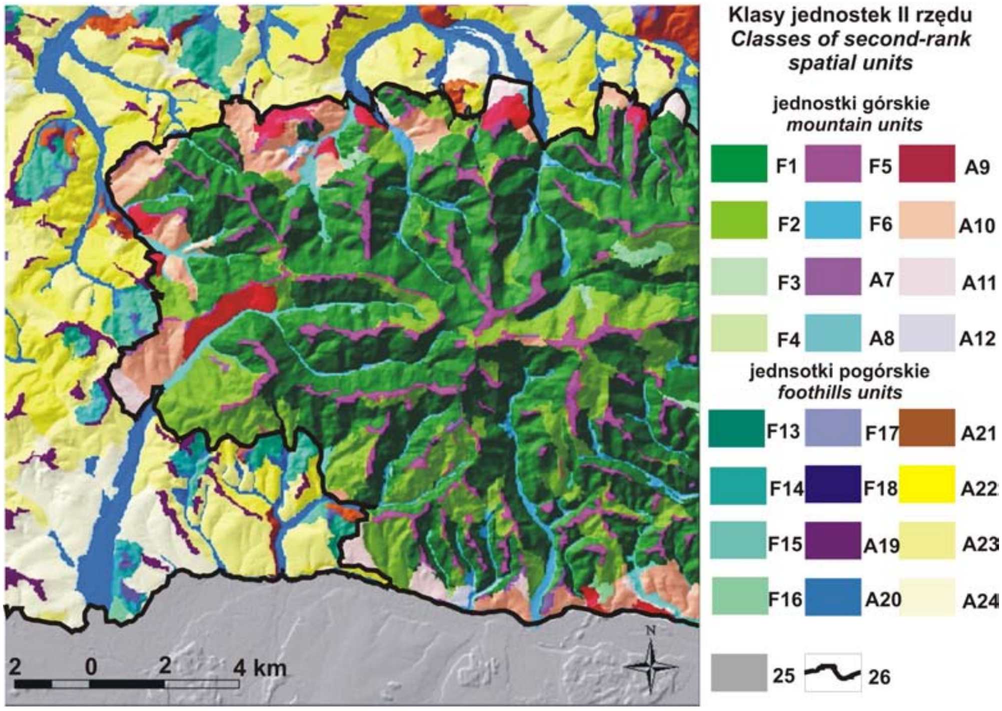

Fig. 2. Types of 2nd rank spatial units & 1st rank unit borders.
F – forest units, A – agricultural units; 1, 9, 13, 21 – steep slopes, 2, 10, 14, 22 – medium-inclined slopes, 3, 11, 15, 23 – gentle slopes, 4, 12, 16, 24 – near-flat slopes, 5, 7, 17, 19 – hilltops, 6, 8, 18, 20 – valley floors; 25 – basins & valley floors, 26 – 1st rank unit borders. ***Source:*** *compiled by the author.*

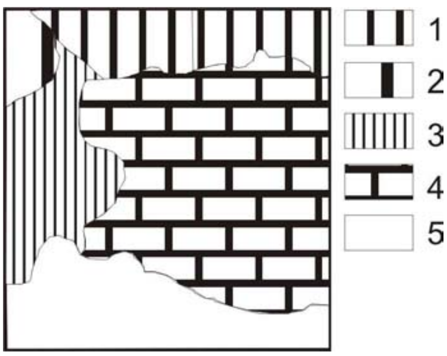

Fig. 3. Geomorphologic unit borders in the study area.
1, 2, 3 – different relief types of foothills,
4 – middle mountain relief type,
5 – basins & valley floors relief type.
Source: *Starkel, 1972.*

The comparison of **middle mountain** and **foothills** units showed significant structural differences (tab. 2). In accordance to the criteria used in the analysis, steep slopes (slope gradient > 15°) were definitely prevailing within the first one, while within the second one there were mainly medium-inclined and gentle slopes. Land use structure of both types was also significantly different (fig. 4, fig. 5). Almost all area of **middle mountain** unit was under forest use, while within **foothills** agricultural land use dominated. Such a spatial pattern of land use is typical for mountainous areas under human impact: people occupy fields most easy to cultivate, and hence most profitable for agricultural use, while very steep slopes remain with forest cover (Troll, 2000).

Relation land use-relief within in the 1st rank units was found to be relatively complex and depended not only on slope gradient. In classes like gentle slopes which occurred in both relief types (fig. 4) the proportion of forest to agricultural use was 3:1 for **middle mountain** units, while for **foothills** units it was inversed and approximately equal to 1:3. It means that land use pattern in the study area was not a conesquence of local slope gradient, but also depended on a wider spatial context (i.e., memebership of a gentle slope unit in the specific super class).

Tab. 2. Morphological characteristic of mountain & foothill area.

BASIC MORPHOLOGICAL CHARACTERISTIC	RELIEF TYPES	
	MOUNTAIN	FOOTHILLS
AREALY PREVAILING TYPES OF SLOPES (NUMBER OF UNITS)	steep slopes 58% (189) medium-inclined slopes 26% (86)	medium-inclined slopes 32% (73) gentle slopes 31% (60) near-flat slopes 13% (25)
AVARAGE RELATIVE ALTITUDE (MAX VALUE)	233 m (560 m)	78 m (171 m)
AVARAGE ALTITUDE OF VALEY FLOORS	729 m a.s.l..	588 m a.s.l.

Source: *compiled by the author.*

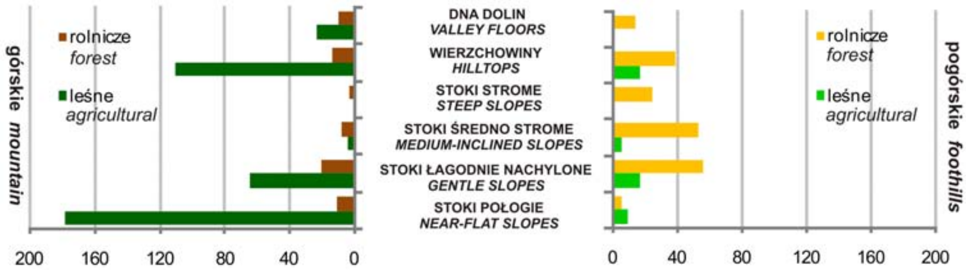

Fig. 4. Number of 2nd rank units within middle mountain & foothills relief types.
Source: *compiled by the author.*

Fig. 5. Areal proportion of mountain & foothill units. ***Source:*** *compiled by the author.*

ADVANTAGES OF OBJECT-BASED ANALYSIS IN LANDSCAPE STUDIES

Segmentation procedure presented in this study resembles the way of traditional 'geocomplex' mapping in the field (demarcating spatial small units, homogeneous in relation to selected variables). The basic processing unit is no longer the geometric pixel, but a meaningful object, which can match real-world entities. But, 'uroczysko' or 'facja' units are not the research goal *per se*; rather, they enable revealing the organisation of the natural system (Czeppe, German, 1978). In the same way, primary segments ('objects primitives') are just a kind of basic processing units. Only additional procedures (e.g., classification, segmentation) taking an advantage of an expert knowledge and considering a significant number of variables, allow building more and more meaningful spatial units ('objects of interest'), which can reflect geographical entities.

Moreover, the object-based approach enables an effective analysis of relationships between segments. Contrary to pixel-based approaches, it gives a possibility to consider each environmental component always in a spatial context (Richling, 1982) and studying a landscape as a multi-scale hierarchical structure (Solon, 2000).

In this study, the object-based analysis allowed distinguishing spatially coherent but structurally heterogeneous units. It means that the 40-years old C. Troll's postulate, that landscape should be considered twofold – as an individual (regional) and typological concept (Richling, 1982) was fulfilled within an automatic processing. So far, the pixel-based approach has provided typological classification i.e. clustering of geometric units (pixels) regarding their similarities. This study showed that it is possible to go beyond a mere typological description and pointed to methods to build spatial units exhibiting a certain degree of heterogeneity. In a smaller scale they are just regional not typological units, which form functional entities.

The hierarchical system of spatial units created in the study showed differenttiation of the environment in several scales. Each hierarchical level gives another set of information about the landscape. For instance, the **foothills** unit, which can be characterised mainly by low inclination, contained some steep slopes as well, recognizable only at the lower hierarchical level (in a finer scale). Furthermore, between units of different ranks there were functional differences as well. Various environmental phenomena appear in different scales, in one scale they can be visible, while hidden in another. The environmental system can be unstable at a lower level but still stay in equilibrium at a higher one (Burnett, Blaschke, 2003).

The procedures used in the study helped to understand a difference between rescaling and resampling (modification of spatial resolution), whereas both seem to be just spatial generalisations. However, when the first one is made essentially by an aggregation of particular objects, the other causes an evident loss of information. That is why even spatially large units should be distinguished on a basis of high resolution data, enabling delimitation of detailed entities and recognition of their characteristic structure (bottom-up approach).

The methodology adopted in this study reduced the subjectivity of spatial units delimitation. Only a part of procedures were strongly affected by researcher's decisions, e.g. selection of data layers, segmentation parameters and thresholds of diagnostic variables for particular classes. Except these, processing (e.g., segmentation, classification) was realised under precisely specified algorithm, consistent within a set of given criteria. The criteria were stored in a log file and, optionally, in a special workflow protocol. Besides, remote sensing data ensure a higher level of objectivism than traditional maps (Widacki, 2001) and automatic analysis guarantees shorter processing time.

Presented paper proposes a methodological framework for spatial data processing which has not been used in Polish landscape ecology before. It reveals some example tools and solutions based on the object-based approach, and emphasizes significance of automatic landscape analysis moving away from pixel-centered view (which is usually uni-scale) to object-based approach, where multiple scale of objects can be explored (Burnett, Blaschke, 2003). Additional variables and thematic layers (e.g., geological map) and increasing accuracy and resolution of spatial data can improve the outcomes of such an analysis. Further studies should aim at working out ways to identify optimal sets of layers, their spatial resolutions and segmentation parameters for specific landscape types and scales of study.

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SUMMARY

Development of remote sensing has contributed to new approaches in landscape ecology, based on GIS technology. However, per-pixel classification, which has been in use since the 1970s, has been criticized as it does not take into account the contextual information, fundamental in geographic analysis. An alternative is object-oriented image analysis, which seems to approximate human perception in digital processing. Its basic processing units are segments (homogeneous groups of pixels) which may represent landscape entities. Contrary to pixels they allow to study e.g. topological and hierarchical relations (providing contextual information).

Object-oriented analysis was used to work out a methodology of environmental analysis. It refers to traditional methods of Polish landscape ecology but take advantage of remote sensing data and GIS tools. As a case study area, Gorce Mts. and surroundings were selected. For the study area, hierarchically structured system of spatial units in three scales was built, which allowed to characterize the study area in respect to morphology and land use. The method enabled an effective landscape analysis through combining an approach specific for human perception with automatic methods, accelerating the research and increasing the level of objectivity.