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Research paper

Determining the parameters of arable land fragmentation

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Abstract: Unfavorable spatial structure of arable land located in Małopolska is a major obstacle in conducting agricultural activity. Arable lands located in the southern part of Małopolska are fragmented, have small area, and irregular shapes. Agricultural activity on land with an unfavorable spatial structure is associated with an increase in production costs, which directly results in lower income of farms. One of the methods of improving spatial conditions is to implement land consolidation works. They allow to organize the spatial structure, increase the area of agriculturally used parcels, while reducing their number. The article presents a new approach in determining the parameters of land fragmentation. GIS tools were used to identify areas with unfavorable spatial parameters. The methodology which allows for the processing, filtration of source data, determination and visualization of land fragmentation parameters is discussed. As part of the research, the Binning method was used, which allows to visualize the phenomenon and simultaneously reduce the data used. In the work, a detailed assessment of land fragmentation parameters was made, which can be used in agricultural land management works. Analyzes have shown that the southern areas of the Nowy Targ County are characterized by intensive fragmentation of arable land. There are also unfavorable parameters related to the elongation and shape of parcels in the discussed areas.

Keywords: GIS, land consolidation, spatial structure, land management, land fragmentation

1. Introduction

Changing land use is a dynamic process taking place almost all over the world. In today's Europe, the phenomenon is related to the changes in arable land use associated with the cessation of agricultural production (Woch and Woch, 2014). It reduces the size of arable land in favor of other forms of use (Noszczyk et al., 2017). One of the effects of this reduction is the emergence of woody vegetation on land that was used agriculturally a few years before (Janus and Bozek, 2018). It is particularly noticeable in post-communist countries in Central and Eastern Europe (Cegielska et al., 2018). The changes in land use are evident, but their causes are extremely difficult to explain. Research is conducted to identify changes and explain their causes. Statistical methods play an indisputable role in determining the causes of changes (Noszczyk, 2018). Arable land conditions affect the profitability of agricultural production. Unfavorable spatial conditions increase production costs, which may result in reducing the profitability of farms (Harasimowicz et al., 2017). The unfavorable conditions include those with a historical, socio-economic and environmental background.

Improving the conditions for agricultural production requires implementing tools that allow effective shaping of rural areas. Legal, economic and technical tools allow changing the conditions that are unfavorable for agricultural production. Such tools include land consolidation works, which allow to improve the conditions for agricultural activity (Janus and Markuszewska, 2019). Land consolidation works not only improve the parameters of arable land, but also contribute to the development of road and water infrastructure (Posiak, 2017). The effects of infrastructure-related works are beneficial to farmers and all inhabitants of areas where agricultural land management works are accomplished.

To improve the conditions for agricultural production, a reliable diagnosis of the current state should be carried out first. There are many criteria to be considered in the analysis of the existing conditions (Gniadek, 2010; Muchová, 2017). The most important are: area, shape, length and fragmentation of arable land (Woch, 2010). Optimal conditions for agricultural production depend on the type of agricultural activity. Regardless of farm's profile, regular forms of arable land simplify works, allowing for the use of modern agricultural machinery (Oksanen, 2013). This contributes to lowering the cost of agricultural production. An important factor influencing the conditions for agricultural production is also the distribution of parcels in a farm (Janus, 2018). Highly fragmented farms are susceptible to larger transport costs.

It is possible to use IT tools to determine the factors affecting the costs of agricultural production (Gasiorowski, and Bielecka, 2014). They enable the development of solutions that are best for agricultural production, the natural environment, and rural residents who are not farmers (Wojcik-Leń et al., 2018) . They allow to calculate parameters describing individual fragments of arable land and the entire farms (Janus and Zygmunt, 2016). Conducting consolidation works without all data describing current conditions may result in incorrect consolidation. In the assessment of conditions prevailing on arable lands, it is possible to use GIS tools (Uyan, 2016). They allow for a reliable assessment of the situation on arable land included in land consolidation (Demetriou, 2018). GIS tools allow to describe spatial structure, what can be used in the determination of arable lands with particularly unfavorable spatial parameters (Leń, 2018). The use of GIS tools enables monitoring changes taking place in spatial structure, thanks to which it is possible to determine the direction the changes in the studied areas may follow. This ensures that consolidation works fit into these changes or allows to effectively counteract (Liu and Yang, 2015). GIS software can also be used in the evaluation of the effects of consolidation work.

The development of technologies for data acquisition and processing means that the process associated with their visualization had to change. The huge amount of data used in research caused a problem related not to the lack of data, but to their excess (Verbesselt, 2015). The problem particularly refers to spatial data represented by points (Dunkel, 2015). Visualization of a large number of data results in a deterioration of information clearness. The data used in studies must therefore be filtered so that the results can be presented in a legible manner. GIS tools allow to visualize data by using the Binning method. This process involves grouping points that are at a certain distance from each other. Currently, the most popular method is based on grouping the objects into the shape of hexagon figures (Adamczyk and Tiede, 2017). The objects created in this way can be grouped into categories, what makes the maps less complicated.

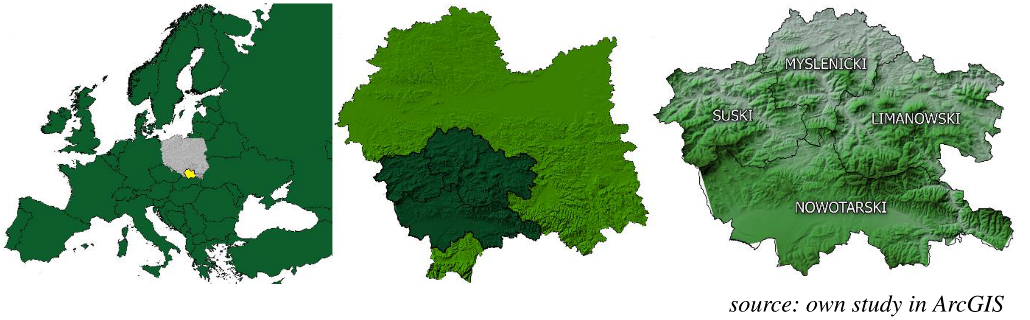
The work attempts to present a universal indicator which would allow to identify areas with unfavorable spatial structure. Using spatial data and GIS tools, an attempt was made to assess spatial conditions for agricultural activities.

2. Data used and methods applied

2.1. Area and data used

The study covered areas located in the southern part of the Małopolska Voivodeship. The subject of the research included cadastral parcels located in the Limanowa, Myślenice, Nowy Targ and Sucha Beskidzka Counties, on which agricultural production took place (Figure 1). Vector data representing cadastral parcels as well as layers describing land use were used both layers had a common coordinate system (EPSG 2180) and data format (ESRI shapefile).

a) b) c)



source: own study in ArcGIS

Fig. 1. Location of the study area (c) in Europe (a), and the Małopolskie Voivodeship (b)

The data of cadastral parcels were obtained from the resources of the Head Office of Geodesy and Cartography (Głównego Urzędu Geodezji i Kartografii – GUGiK) in the ESRI shapefile format, separately for each of the studied counties. As part of the cooperation between GUGiK and the Agency for Restructuring and Modernization of Agriculture (ARMA), the Integrated Administration and Control System (IACS) was created, which made it possible for farmers to obtain subsidies from the European Union.

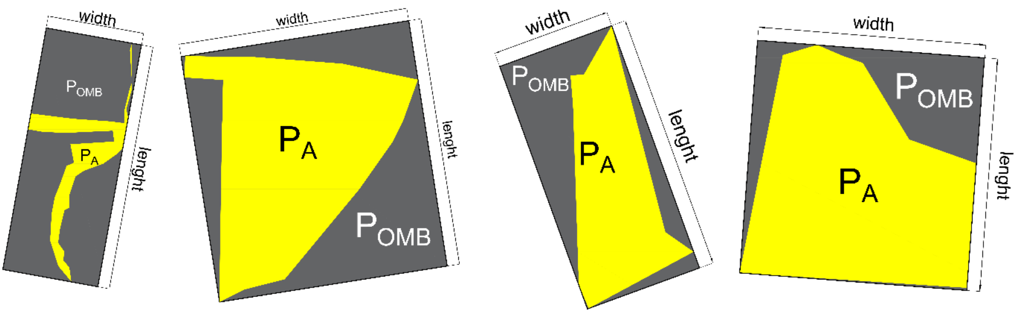
The basic element of this system was the Land Parcel Identification System (LPIS), which contained approximate information on the boundaries of cadastral parcels. These data could only be used for the approximate identification and spatial location of parcels as well as for estimating their area (Zaremba and Zoń, 2007). In the period of 2016–2018, the data could be downloaded from geoportal.gov.pl. All data had a homogeneous structure, thanks to which there was no need for additional works related to the preparation of data for analyses. The obtained data allowed for the implementation of the research methodology.

2.2. Methods

The parameters of land fragmentation were determined with the use of GIS tools in the proposed methodology. It consisted of three tasks: processing and filtration of source data, determination of land fragmentation indices, and visualization of results.

In the first stage, the source data underwent processing and filtration. The data represented by cadastral parcels of four counties were merge into one layer. The layer of cadastral parcels was intersected with arable land included in the layer containing the information on land use. This made it possible to limit the set of parcels to arable land, thanks to which the analyses allowed to determine the parameters of arable land fragmentation. Keeping the original number of parcels would distort the results of the analyses as the research would cover all areas and not only arable land. As a result of the intersection, vector objects representing arable lands having boundaries in line with cadastral parcels were created. In order to avoid the occurrence of several vector objects representing arable land on one cadastral parcel, the objects were aggregated. Parcel's number was the parameter of the aggregation, thanks to which the objects located on one parcel were merged into one object. The aggregation tool joined objects within one parcel without changing their geometry, hence all parameters describing arable land were calculated correctly. Next, an attribute that corresponded to the arable land area in the parcel was created. It was then linked to the source layer of parcels by a common identification number. The areas of arable land in the parcels were compared with the areas of the parcels, and the results were then multiplied by 100. Thanks to this, the percentage share of arable in the parcels ($P_{al\%}$) was obtained.

The next stage of data processing was related to the calculation of parameters describing the shape of a parcel. There are many methods of calculating the parcel's shape, allowing to find their length and width (Janus et al., 2016; Harasimowicz et al., 2017; Kwinta and Gniadek, 2017). Most methods, however, have difficulties in calculating the parameters of elongated parcels as well as those of irregular shapes. Built-in tools of GIS software, both commercial and free, also interpret the parameters of such parcels incorrectly. The proposed methodology, however, allows to use the obtained results to identify parcels that hinder the consolidation work. The Oriented minimum bounding box tool, included in the QGIS software, was used to calculate the parameters related to the shape of a parcel. It allows to create for each object a vector layer of rectangular quadrangle, which contains all the vertices belonging to the object. In a situation where the parcel has shape similar to a square or a rectangle, an almost identical object is created, as in the case of a source parcel. When processing parcels of irregular shapes, a rectangular object, containing all the vertices, is created, but the parameters describing the shape do not represent the actual shape of the parcel. Figure 2 shows the result of the OMB tool for exemplary parcels of land located in the research area. After using the Oriented minimum bounding (OMB) tool, attributes such as identification number, height, width, angle, and area were obtained. They were linked to cadastral parcels, similarly as in the case of combining the area with a parcel through a common identification number. Then, the ratio of width and height attributes and the ratio of parcel area and the area represented by the object created in the Oriented minimum bounding (OMB) software were created. The last attribute was multiplied by 100, which resulted in the ratio of the parcel area to the OMB surface expressed in percentages (P_{sq}).



source: own study in ArcGIS

Fig. 2. Example of the Factor shape square application for parcels located in the research area

After the completion of data processing, filtration was initiated. Its aim was to eliminate parcels that did not belong to the arable land criterion. The filtration was completed in two variants, the first one included parcels whose area was smaller than 0.1 ha. If arable land occupied less than 75% of a parcel smaller than 0.1 ha, and the ratio of the parcel area to the area occupied by the OMB object was less than 20%, the parcel was excluded from further calculations. The second approach included parcels whose area was equal or exceeded 0.1 ha. If the percentage of parcel's arable land was smaller than 50% and the value of P_{sq} was less than 10%, the parcel was excluded from further calculations. By using filtration, parcels that did not belong to arable land, including roads or built-up areas, were excluded. The implemented methodology which consisted of processing and filtration of data allowed for the calculation of indices describing land fragmentation.

The determination of land fragmentation parameters based on built-in GIS tools was completed for several reasons. Firstly, the chosen methodology was to determine areas with unfavorable conditions for agricultural activity. In the indicated areas, the implementation of consolidation works, taking into account the developed factors, would improve agrarian conditions. Secondly, the methodology was aimed at showing the possibility of using GIS tools in creating such factors.

After processing the source data and their filtration, the calculation of land fragmentation factors was initiated. The factor defining land fragmentation parameters consisted of three separate factors, the sum of which allowed to determine the intensity of land fragmentation in the studied area.

The first factor was to determine the state of the agrarian structure. Factor of agrarian structure (F_{as}) takes into account parcel area and the extent to which its land is used for agriculture. The first element is related to the area of an agricultural parcel. The highest value, equal to 1, of the factor of agrarian area (F_{area}) is obtained by parcels with area smaller than 0.1 ha. The factor of agrarian area (F_{area}) value of 0.9 was assigned for parcels with area of 0.1–1.0 ha. The value of 0.8 was given to parcels with area of 1–2.5 ha. The value of 0.7 corresponds to parcels with area of 2.5–5.0 ha, and parcels with area of 5.0–10.0 ha received value equal to 0.6. The lowest value, equal to 0.5, was given to parcels of area greater than 10 ha, because on such parcels there are no difficulties in conducting agricultural activities caused by area.

The second element of the factor of agrarian structure (F_{as}) is related to the percentage of arable land located within the border of a single parcel. If the area of arable land occupied 50–75% of the total area of the parcel, it received the value equal to 1. Parcels on which arable land occupies between 75 and 90% were ascribed the attribute equal to 0.75. Parcels where arable land area exceeded 90% received value of 0.5. Table 1 contains the values of the elements that constitute the factor of agrarian structure.

Table 1. The values of the factor of agrarian structure

$$F_{as} = F_{area} \cdot P_{al\%}$$

where:

F_{as} – factor of agrarian structure
F_{area} – factor of agrarian area
$P_{al\%}$ – percentage of arable land

F_{area} – factor of agrarian area		$P_{al\%}$ – percentage of arable land	
area	value	percent	value
< 0.1 ha	1.0	$< 75\%$	1.0
0.1–1.0 ha	0.9	75–90%	0.75
1.0–2.5 ha	0.8	$> 90\%$	0.5
2.5–5.0 ha	0.7		
5.0–10.0 ha	0.6		
> 10 ha	0.5		

source: own study

The second factor constructed with the use of GIS tools was aimed at identifying parcels with a shape deviating from a square. Factor shape square (F_{ssq}) depends on two elements. The first factor is the ratio of the width to the length of a parcel. These attributes were obtained by using the Oriented minimum bounding tool while processing the source data. The obtained results can be divided into two categories: when the ratio of width to length takes values equal to and less than 1; and when the ratio takes values equal to or more than 1. This is caused by the way the tool works: it perceives the edges of the parcels facing north or in direction close to north as the length of the parcel. Therefore, if the attribute exceeded the value equal to 1, the length–width ratio was calculated, what caused all the results to be equal to or less than 1. Basing only on the length–width ratio would result in identical results for parcels with regular shape and for those that are elongated, but which have irregular geometry. Due to errors in identifying parcels of irregular shape, a second factor was introduced. It is related to the percentage ratio of parcel area to the area of the OMB object (P_{sq}). The more the shape of a parcel resembles a square, the closer the value of the factor is to 1 (see Equation (2)). In addition, the elements included in the factor shape square (F_{ssq}) were weighted so that the values correctly described the situation prevailing in the studied area in terms of the shape of the parcel. The first element associated with the length–width ratio was given a weight of 0.6 and the second equal to 0.4 (see Equation (1)). The dependence of factor shape square (F_{ssq}) two parameters means that only square-like parcels get lower values. The more complicated the geometry of a parcel, the closer the value of the coefficient is to 1. The work attempts to present a universal indicator which would allow to identify areas with unfavorable spatial structure. One of the indicators was factor square shape. Its values were close to 1 when the parcel was of a shape close to a square. The assumed optimal value was intended to present the research methodology. GIS tools allow to classify the obtained results in such a way that the final indicator takes into account the appropriate ratio of the parcel sides. It is also possible to parameterize the results, thanks to which we can choose the most advantageous solution related to the optimal proportion of parcels' shape. Putting the developed methodology into practice, it is necessary to adjust the optimal proportions to fragmentation parameters and the form of use. The optimal parameters of a parcel are primarily influenced by area. To large extent, the area is related to the location of arable land. Optimal parameters of agricultural parcels located in Southern Poland will be different from those in the central or northern part of the country. The conducted studies differ in terms of optimal proportions: some consider the best ratio of width to length of parcels to be 1:3 – 1:6 and other propose a ratio of 1:2 as optimal (Gniadek, 2013, Noga, 2005, Demetriou et al., 2013). An unambiguous solution to the problem of which ratio should be optimal is extremely difficult. Such choice must be preceded by the analysis of other conditions occurring in the area. This work proposes a universal solution, which, however, must be verified during land consolidation works.

$$F_{ssq} = \left[0.6 \cdot \left(1 - \frac{P_{width}}{P_{length}}\right) + 0.4 \cdot \left(1 - P_{sq}\right)\right], \tag{1}$$

$$P_{sq} = \frac{P_A}{P_{OMB}}, \tag{2}$$

where:

P_{width} – the width of a parcel,
P_{length} – the length of a parcel,
P_{sq} – ratio of parcel area to the area of the OMB object,
P_A – area of parcel,
P_{OMB} – area of the OMB object.

The third and last factor included in the factor determining land fragmentation is related to the spatial distribution of arable land – Factor localization of arable land (F_{loc}).

It allows to determine areas where the intensity of the phenomenon undergoes changes. As a result, both areas with an increased and reduced number of agriculturally used parcels can be identified. The previous calculations of the elements of land fragmentation factor were based on the assignment of proper attributes to a cadastral parcel. To calculate the intensity of the phenomenon, it was required to convert cadastral parcel from the polygonal form to the point form. Using the ArcMap Polygon to Point tool, objects' centroids were created, with the condition that the centroids had to be inside the source polygon. Then, the analyzed area was divided into smaller parts. A grid consisting of hexagons was created, each having a area of 1 km^2. For each hexagon, the number of parcels within its boundary was calculated, as well as the average value of $F_{al\%}$ and factor shape square (F_{ssq}). To achieve this, the ArcMap Join and Relates tool was used, which calculated the parameters of parcels' centroids based on them. This allowed to calculate the third factor, describing spatial diversity of arable land.

$$F_{loc} = \frac{G_x - G_{avr}}{G_{max} - G_{avr}}, \tag{3}$$

where:

G_x – number of parcels' in polygon with hexagon shape,

G_{avr} – average number of parcels' in polygon with hexagon shape,

G_{max} – maximum number of parcels' in polygon with hexagon shape.

Factor localization of arable land (F_{loc}) takes into account not only the number of parcels per 1 km^2, but by including the average and maximum value, it allows to compare these values to all values occurring in the entire analyzed area (see Equation (3)). With the increase in the area of the Factor localization of arable land (F_{loc}), it is possible to determine the areas with both increased and decreased intensity of the land fragmentation phenomenon.

The last stage related to the factor of arable land fragmentation required combining the previously calculated factors. Each of the developed factors can be used independently, taking in such cases values 0–1, but only combining them all in one allows to determine areas where arable land fragmentation occurs. Each of the factors has been given proper weights, so that the most important factors showing the fragmentation of land are taken into account. The first factor, factor agrarian structure (F_{as}), received the highest weight, equal to 0.4. The size of a parcel directly indicates the costs related to agricultural production. With the increase in the area of a parcel, the production costs decrease, which means that agricultural production on large area fields is less expensive. (Hiironen and Riekkinen, 2016; Lu et al., 2018). Factor shape square was given a weight equal to 0.3. It allows to determine elongated parcels with complex geometry. The last, F_{loc} factor, which helps to determine areas where the intensity of arable land occurrence is higher than in other analyzed areas, also received a weight equal to 0.3. The weights of individual factors constituting the factor of arable land fragmentation are shown in Equation (4).

$$F_{frag} = 0.4 \cdot F_{as} + 0.3 \cdot F_{ssq} + 0.3 \cdot F_{loc}, \tag{4}$$

where:

F_{frag} – factor of arable land fragmentation,

F_{as} – factor of agrarian structure,

F_{ssq} – factor shape square,

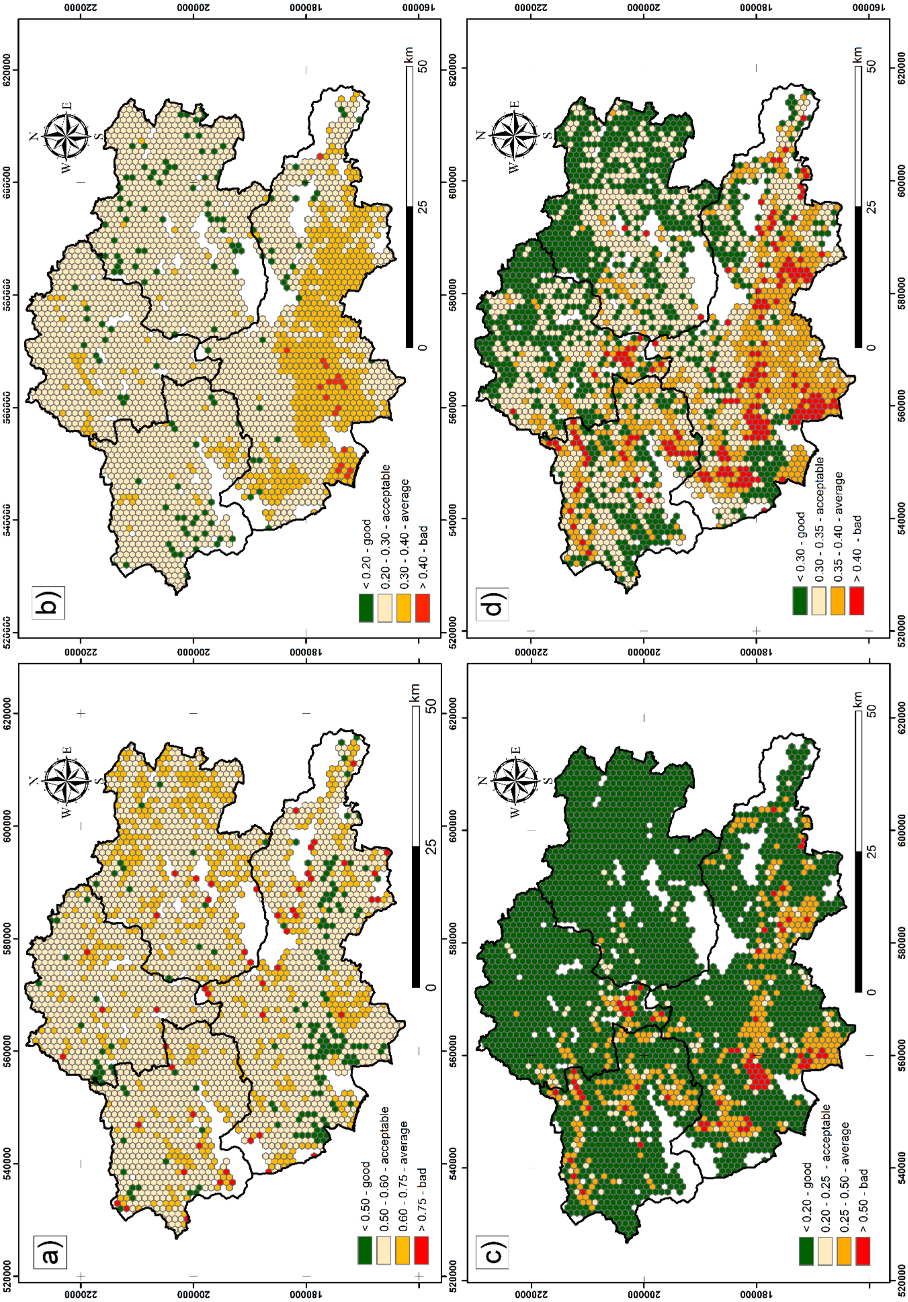
F_{loc} – localization of arable land.

The last element of the methodology was to visualize the obtained results. To present the results in a transparent manner, while maintaining the crucial information, it was chosen to use the vector hexagon grid. (Birch et al., 2007). Compared to other grids, such as those of squares or triangles, the one created with the use of hexagons causes each point included in a single hexagon to be closer to the center (Adamczyk and Tiede, 2017). The area of each hexagon included in the vector grid was equal to 1 km^2. The Generate Tessellation tool was used to create the grid, and the esri shapefile format was selected as the grid format. This allowed to create a map of spatial distribution of the phenomenon, that is the fragmentation of land. The values of land fragmentation factor presented with the use of hexagons by calculating average fragmentation parameters for each of them. This allowed not only to increase the readability of information, but, above all, to limit the amount of data used in the study. The calculation of the average values of hexagon factors resulted in the use of a rating scale that allows to identify areas with poor spatial structure. The generalization of data, results or the choice of the scale of the study may cause the loss of the local values which deviate from average values in a given area. This may lead to its erroneous examination by underestimating or overestimating (Bozek and Janus, 2017; Bozek et al., 2018). For this reason, the threshold values for each of the factors were created to counteract this and allow to identify areas with unfavorable spatial parameters.

All stages associated with the determination of land fragmentation parameters completed in both the ArcGIS and QGIS software were automated. For this purpose, the Model Builder tool included in ArcGIS and The graphical modeler tool included in QGIS were used. The construction of models that allow for the automation of the methodology does not require specialized knowledge in programming; it is achieved through the use of a graphic interface (Pochwatka et al., 2017). Thanks to automation, it is possible to apply the methodology to any area in order to obtain land fragmentation parameters.

3. Result and discussion

In the research, 1,617,809 cadastral parcels located in Limanowa, Myślenice, Nowy Targ and Sucha Beskidzka Counties were analyzed. After data filtration, related to the elimination of parcels that did not meet the criteria specified in the methodology, the number of objects decreased to 816,456. The most numerous group consisted of parcels with area less than 0.1 ha i.e. those on which agricultural production is difficult. The largest area was occupied by parcels with area between 0.1 and 1.0 ha. For each cadastral parcel, the values of land fragmentation indices were calculated. Due to the large amount of data to be visualized, the results were presented as average values of indices for cadastral parcels within the boundary of a single hexagon with area equal to 1 km^2.



source: own study in ArcGIS

Fig. 3. Factors describing the spatial structure, being part of Factor of arable land fragmentation (d) factor of agrarian structure (a), factor shape square (b), and factor localization of arable land (c)

The first factor describing the agrarian structure had hexagon values ranging from 0.3 to 0.9. There were clusters of areas that showed good, acceptable, average, and bad agrarian structure in the whole area. Good agrarian structure occurs in the southern part of the Nowy Targ County, the acceptable one occurs almost all over the analyzed area. The average signaling that one should observe changes in agrarian structures in the studied areas occurs in the eastern part of the Sucha Beskidzka County and in the south-central part of the Nowy Targ County. Bad agrarian structure can be found in the northern part of the Nowy Targ County (Figure 3a).

The second factor describing the parameters of land fragmentation took into account the elongation and shape of a parcel. Factor shape square (F_{ssq}), like the first factor, adopts a scale of values, which indicates the occurrence of good, acceptable, average, and bad land fragmentation conditions. The southern part of the analyzed area is dominated by the average values of the Factor shape square (F_{ssq}). In the majority of the Nowy Targ County there are average conditions associated with the elongation of parcels and their irregular shape. The bad Factor shape square (F_{ssq}) values occurs in the south-western part of the Nowy Targ County (Figure 3b).

The last independent factor, Factor localization of arable land – F_{loc}, shows how the intensity of cadastral parcels occurrence in the studied area changes. It allows to identify values that deviate from the average values characteristic for the whole area. The maximum number of parcels per 1 hexagon was 1,752, and the average number in a hexagon was equal to 162. The largest factor value were met in the areas located in the south-western part of the Nowy Targ County and in the southern part of the Myślenice County. The western and southern part of the studied area indicates an increased intensity of parcels occurrence, which proves large fragmentation of arable parcels (Figure 3c).

The sum of all factors allowed to determine the parameters of land fragmentation in the analyzed area. The range of the factor values ranged from 0.18 to 0.59. Determined were the areas where the factor showed good, acceptable, average, and bad values. As in the case of the previous factors, it reached the highest value in the south of the Nowy Targ County. These areas indicate that there is a need to implement agricultural land management works (Figure 3d).

The study analyzed the arable land assuming that it covers single parcels. The study did not include data relating to registration units. The methodology allows to complete research including data on agricultural farms.

4. Conclusions

GIS software can be used in the process of arable land spatial structure analysis. It is a valuable tool that can improve the determination of land fragmentation parameters. It allows to prepare source data and then analyze arable land fragmentation. The use of GIS tools included in free and commercial software allows to visualize the obtained results. The results of research can be presented taking into account the area and the scale of the study, which leads to better presentation of the results. This is particularly important for the studies on large-scale phenomena, where the large quantity of data prevents the presentation of all results in a direct form. The proposed methodology can be implemented in commercial or free GIS environment. Each GIS environment offers all the tools required to conduct the research. This makes the proposed methodology universal. The type of software does not limit the possibility of conducting research on the spatial structure of arable land. The proposed methodology can be applied to any area, both those covering single cadastral districts and entire counties. GIS tools make it possible to adjust the methodology depending on the area under study. By means of easy calibration of the results, it is possible to determine threshold values beyond which cadastral parcels will require interventions within the framework of land consolidation works.

The study analyzed the arable land assuming that it covers single cadastral parcels. The study did not include data relating to registration units. The constructed methodology allows to complete research including data on farmsteads. GIS software makes it possible to automate processes related to the determination of land fragmentation parameters. Automation of the calculation of land fragmentation factors allows also to determine changes occurring in spatial structure of land by applying the methodology for data from different time periods. The development of spatial indicators with the use of GIS tools allows for a quick and reliable way of obtaining information on the spatial structure of arable land. Consequently, it is possible to apply the methodology to any area. It makes land fragmentation indices a universal tool that can improve agricultural land management works. The results of the research can be used in every stage of land consolidation works. They can be applied to identify areas with unfavorable spatial structure. The developed analyses can be helpful during structural reorganization. They make it possible to determine parcels that require shape correction due to unfavorable geometry.

Acknowledgments

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