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ANALYSIS OF LAND USE CHANGE IN SELECTED METROPOLITAN AREAS IN POLAND BASED ON REMOTE SENSING DATA

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Summary

The aim of the study was to diagnose the main trends of changes in land cover in selected communes of Polish metropolitan areas. Detailed studies were conducted in deliberately selected housing estates located in the core of metropolitan area (at least one housing estate) and communes located directly at the border of cities and located on the outskirts of metropolitan areas. The examined communes also differed in the quality of natural conditions of agricultural production. The study used LANDSAT 5 TM and RapidEye satellite images from three limited-time registrations (1996/1999, 2011, 2016/2017). On the basis of remote sensing data, changes in land use were specified by presenting them in a graphic form as compilation of numerical maps. The analyses were performed on processed images (colour compositions), which were subjected to supervised classification using the maximum-likelihood technique. The quality control of supervised classification showed accuracy of 89.3% for LANDSAT 5 TM scene analyses and 91.8% for RapidEye images. Kappa coefficient for the discussed classification was: 0.84 (LANDSAT TM) and 0.89 (Rapid Eye). The results obtained for individual metropolitan areas allow to identify the directions of changes (Land Use Change Cover) taking place in them, with consideration to specificity of each of them.

Keywords

land cover • metropolitan area • satellite data

1. Introduction

Metropolitan peri-urban areas (MPU) are currently undergoing major changes in many developed countries. Expansion of urban areas results in change of population composition, business structures, employment, and also land cover [Busck et al. 2006]. Changes taking place in the core of metropolitan areas, and also in their vicinity, should be under constant control. It is related to the rational management of space in these areas. One way of such supervision is to identify changes that have occurred so far in a given area and to predict direction of its further development; such approach enables to target it in accordance with sustainable development [Chaba et al. 2015].

Monitoring changes has become possible with development of satellite photo-grammetry and remote sensing. Development of remote sensing techniques, in particular the increase in the temporal and spatial resolution of remote sensing images, made it possible to conduct both detailed research on small areas and creation of global studies of changes in land cover and use. In places where these changes occur very quickly, they can be observed in real-time [Verburg et al. 2009].

Land use/land cover changes (LULCCs) are the result of interaction of complex socio-economic processes, including urbanization and environmental conditions [Busck et al. 2006]. Globally, studies on drivers of LULC emphasize on forests most and consider agriculture less. Nevertheless, in advanced countries, including Europe and North America a major phenomenon is the decline of agricultural land both due to settlement and infrastructure development and due to afforestation [Meyer and Früh-Müller 2020]. Many studies emphasize that in metropolitan areas a special place is occupied by agricultural lands, which are also subject to the greatest changes [Rolf et al. 2018].

In Poland, the share of agricultural land in the cores of metropolitan areas (MA) is over 30% of their total area, i.e., twice as much as built-up and urbanized areas [Sroka et al. 2018]. In the outer zone communes of metropolitan area, the percentage of agricultural land exceeds 60%, i.e., it is more than the national average [Meyer and Früh-Müller 2020]. Nevertheless, in many studies [Lorens and Martyniuk-Pęczek 2010, Krzyk et al. 2013, Sroka 2018] it is emphasized that in Polish planning practice (sub-) urban agricultural land is a reserve for areas intended for housing construction. In years 2010–2014 in Polish metropolitan areas, about 0.59% of agricultural land was converted annually for non-agricultural purposes, and the dynamics of this process significantly depended on the location of land in relation to the core of the metropolitan area [Sroka 2018]. The cited research [Sroka 2018], and also the study by Busko and Szafranska [2018] showed a particularly disturbing trend of conversion of agricultural land of particularly excellent quality and suitability for agricultural production (land classes I-III) for non-agricultural purposes.

Issues related to factors responsible for the directions of land use changes are often discussed in the literature. Scholars identified multiple drivers affecting LULCCs: demographic, economic, technological, institutional, socio-cultural, and location-related factors [Meyer and Früh-Müller 2020]. Nevertheless, the most important of them include Economic, institutional, and biophysical location-based factors [van Vliet et al. 2015]. These drivers are analysed using various theoretical frameworks, ranging from Boserupian intensification theory, smallholder subsistence land use, through institutional theories, and ending with land rent theories [Meyfroidt et al. 2018, Satoła et al. 2018].

In this study, the LULCCs change analysis was based on the assumptions of the theory of economic rents [Diogo et al. 2015]. Alonso [1964], but also von Thunen and Ricardo much earlier emphasized that the way land is used is determined by economic rents [Ustaoglu et al. 2016]. According to the Alonso model [Alonso 1964], the differences resulting from the location of specific activities in relation to the core cities are a derivative of their utility/profitability. In close proximity to the city centre, land prices are extremely high (strong competition for land), hence only the most profitable activities generate sufficiently high profits/income to be able to cover the costs of the involved factors of production (mainly land). As noted by [Wastafele and Zhang 2016], as well as [Mazzocchi et al. 2013] agriculture, as a low-profitability sector, usually loses the competition for land. The natural conditions of agricultural production may also affect LULC changes [van Vliet et al. 2015]. According to Ricardo's models, favourable farmland biophysical parameters (including soil quality, water conditions, climate, slope, and elevation) and related additional land productivity income (economic rents) and wider choice of production profile [Ribeiro et al. 2014] influence the dynamics of LULCCs by limiting the reduction of agricultural land.

The aim of the study was to diagnose the main trends of land cover changes around urban agglomerations, with particular emphasis on arable land and grassland. The analysis was conducted on the example of selected communes of the Warsaw, Krakow, Wroclaw, and Tri-City metropolitan areas over the period of twenty years (1996–2016).

The publication reviews the literature on environmental monitoring, characterises the source materials on which this study is based, as well as the image classification method used, and the results chapter includes land use maps of the studied metropolitan areas (MAs) drawn from Landsat and RapidEye images.

2. Literature review on environmental monitoring

Rational spatial management requires reliable information on land cover and use and changes that take place in this regard. Significant increase in the availability of remote sensing images in recent years (especially the emergence of new high-resolution sensors) and development of processing and analysing information recorded on them, create new opportunities for use of multi-time remote sensing images in monitoring changes in the use of space [Drzewiecki 2008].

An example of using remote sensing images to monitor transformations of space in urbanized areas on a local scale is, implemented by the EU Community Research Center, MOLAND project (Monitoring Land Cover/Land Use Dynamics). This program was a continuation of the previously implemented (since 1998) MURBANDY (Monitoring Urban Dynamics) program. The aim of the MOLAND program was to assess, monitor and model the past, present and future development of cities and regions from the point of view of sustainable development [Barredo et al. 2003].

Remote sensing image data constitute an objective record of the landscape, a comprehensive registration of its components and relations, especially spatial ones, between them [Mularz et al. 2007]. They have different cartometric and photointerpretation potential, determined primarily by the nature and resolution of imaging that enable their use in the development of coverage and land use maps at various scales and with a different degree of detail in separations [Drzewiecki 2008]. These topics were also taken up by Bruzzone and Serpico [1997], Lu et al. [2004], Peiman [2011], Schneider [2012], Tian et al. [2013], Zhu and Woodcock [2014], Tewkesbury et al. [2015], Grabska [2017].

Changes taking place in the studied area can be observed and analysed on the basis of available, free of charge (e.g., SENTINEL-2A, ESA, LANDSAT) and commercial (e.g., WorldView-2, DigitalGlobe, RapidEye) satellite systems. These systems perform continuous observations of the Earth's surface, acquiring images with high spatial and spectral resolution, enabling the development of up-to-date Land Use and Land Cover maps (LULC) [Wężyk et al. 2016].

Long-term remote sensing images are not only an invaluable tool for monitoring changes taking place on the earth's surface, but also, as demonstrated by studies conducted under the MOLAND program, may provide data necessary to build advanced models to support spatial policy on a local, national, and European scale [Drzewiecki 2008].

Another pan-European earth monitoring program is GMES (Global Monitoring for Environment and Security). GMES is an initiative of the European Union, implemented jointly by the European Commission and the European Space Agency; its aim was to support the implementation of the sustainable development policy [Lewiński 2007]. The program was implemented with the initiation of the so-called Fast Track Services (FTS) for three application areas: land surface monitoring, sea monitoring and extraordinary environmental threats [GMES Fast Track Land Monitoring Core Service 2007]. The program, the implementation of which was started as part of the fast track for the so-called continental component, is a continuation of the CORINE Land Cover program.

The effect of such programs is, among others complete Urban Atlas: delivery of land use/cover maps of major European urban agglomerations, which was to be created by the end of 2009 in accordance with the assumptions of the tender announced by the European Commission. Among the three hundred and five European cities it took over, there were 27 Polish cities: Warsaw, Lodz, Krakow, Wroclaw, Poznan, Gdansk, Szczecin, Bydgoszcz, Lublin, Katowice, Bialystok, Kielce, Torun, Olsztyn, Rzeszow, Opole, Gorzow Wielkopolski, Zielona Gora, Jelenia Gora, Nowy Sacz, Suwalki, Konin, Czestochowa, Radom, Plock, Kalisz, and Koszalin [Urban Atlas LUZ Priority List 2007].

The first inventory of land cover made in Poland within CORINE Land Cover project concerned reference year 1990. The basis for development of land cover database CLC1990, were images taken with TM scanner by Landsat 4/5 satellites. Satellite images were acquired in 1986–1995. The CLC1990 land cover was presented on a wall map developed at a scale of 1:500000. Subsequent studies for the whole Poland were conducted in 2000, 2006, 2012 and 2018. The unit responsible for the implementation of subsequent projects (CLC2000, CLC2006, CLC2012, CLC2018) in Poland was the Chief Inspectorate for Environmental Protection.

Within the framework of these projects, the data contained in the national database, obtained during the earlier inventory, were updated and the CLC-Change land cover change database was developed, illustrating the dynamics of land cover changes in Poland in individual periods.

In case of CLC2000 project, the source of information were satellite images taken with ETM+ scanner by Landsat 7 satellite. 30 m spatial resolution channels were used for interpretation. In the CLC2006 project, it was also intended to use images taken by the Landsat 7ETM+ satellite to provide comparable data. However, a technical failure of the sensor prevented the use of images acquired by this satellite. Eventually, images taken by Indian IRS satellite and French SPOT-4 were used, but they have slightly higher spatial resolution (20 m) and different spectral resolution. The following datasets were used to develop CORINE Land Cover 2012 databases: images from SPOT4/5 and IRS-P6 satellites from 2006 +/− 1 year, images from RapidEye and IRS-P6 satellites from 2011 and 2012. Satellite imagery from RapidEye and IRS-P6 satellites acquired in 2011 and 2012 and from Sentinel-2 and Landsat-8 satellites acquired in 2017 were used to map land cover/land use changes for the period 2012−2018 and to develop a unified CLC2018 database.

The study of changes in land cover and use on the basis of multi-time remote sensing images has been conducted for many years both in Poland and abroad [Dramstad et al. 2002, Hietel et al. 2004, Ciołkosz and Bielecka 2005, Lewińska 2011, Niedzielko and Lewiński 2012, Hussain et al. 2013, Zhu and Woodcock 2014, Tewkesbury 2015, Cegielska et al. 2018].

In remote sensing studies, land cover is observed, and on its basis, use is concluded. Therefore, legends are constructed in such way that specific subdivisions fit both concepts, comparing in a given class a specific type of land cover corresponding to its use. These types of legends are widely used in research, the subject of which is referred to as Land Use/Land Cover [Civco et al. 2002, Chen et al. 2003, Cakir et al. 2006, Wężyk et al. 2016].

Comprehensive review of the methods of detecting changes based on satellite images has been conducted by Lu et al. [2004]. They divided the methods into seven general groups: algebraic methods [Rossiter 2014], transformations [Bruzzone and Prieto 2000, Carvalho et al. 2011], classifications [Ahmad and Quegan 2013, Abburu and Golla 2015], models [Vieira et al. 2012], application of geographic information systems [Wężyk et al. 2016], visual analysis [Arvor et al. 2013] and other approaches [Fuller et al. 2003, Coppin et al. 2004, Boldt et al. 2012, Xu et al. 2018].

Among those listed is the classification method used in this study. The most popular method is the so-called post-classification analysis. It is based on comparing two independent classifications conducted on two images of the same area. This method was applied by: Civko et al. [2002] – unsupervised land cover classification using the ISODATA method, using Landsat images; Bauer et al. [2003] – a study of land cover changes in the metropolitan area of Minneapolis and St. Paul based on Landsat data, comparing own complex classification methods; Michałowska and Głowienka-Mikrut [2010] − study of land cover changes in the Slowinski National Park using the highest-probability classification method, carried out on images from Landsat satellites; Prakasam [2010] – supervised land cover classification in photos from the TM sensor. Comparison of two independent classifications is favoured by Bochenek [2004], comparing the accuracy of this method with the methods of comparing the values of spectral reflection from two recording periods, comparing the values of green indices, principal components analysis, vector of change analysis, classification of combined images [Niedzielko and Lewiński 2012]. The comparison was conducted on high-resolution satellite images of a fragment of the Warsaw agglomeration. Another type of classification are methods that use the so-called artificial intelligence, e.g., neural networks. This type of classification was applied to detect land cover changes in the Millestone River area of New Jersey [Civco et al. 2002].

3. Materials and methods

3.1. Source data

Currently, the primary source of information about the environment and changes that occur in it are satellite images. When studying changes in land cover, the most important values of satellite images are synoptics, high repeatability of imaging the same areas, low acquisition cost and automation of the process of interpreting their content [Bochenek 2004]. A key factor when using this type of data is their availability. The Landsat mission has been providing data about the Earth continuously for forty years. All archival and up-to-date images are available to any user worldwide, free of charge. Sensory Thematic Mapper and Enhanced Thematic Mapper + located on satellites moving in a heliosynchronous orbit are the source of multispectral images with a terrain resolution of 30 m [Yuan et al. 2005, Ciołkosz and Poławski 2006, Wulder et al. 2016].

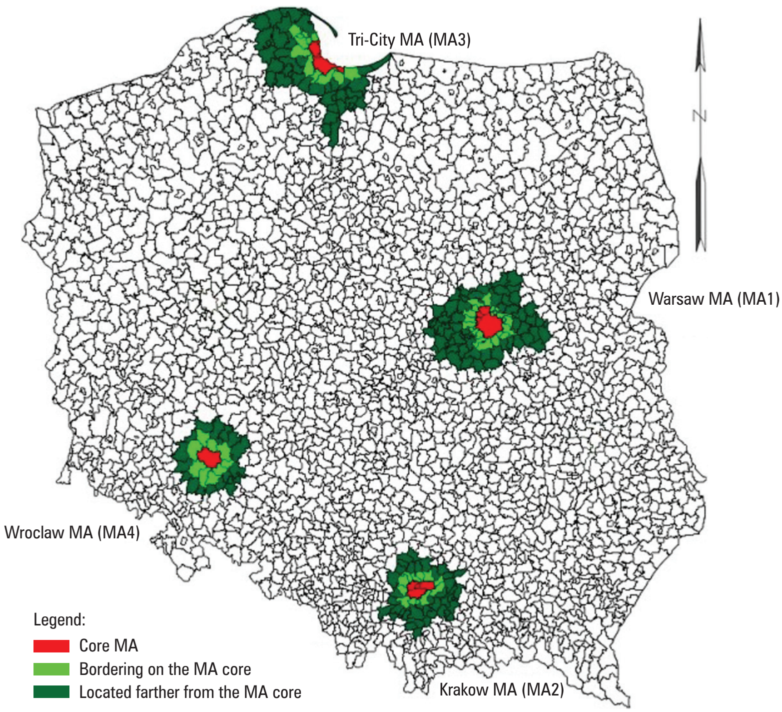
Source data from three different time periods were used in the research. The first one included LANDSAT 5 TM (Thematic Mapper, NASA) satellite scenes from 1999 (Warsaw and Wrocław), 1997 (Tri-City) and 1996 (Krakow). The second period includes RapidEye images from 2011 for all the metropolitan areas studied. While the third one included RapidEye's images from 2016 (Wrocław and the Tri-City) and 2017 (Warsaw and Krakow). The selection was based on the availability of good-quality images, with the smallest possible share of clouds, and the years for which images taken at a similar time of the year were available. The selection of scenes in the same month (VIII) but different years was important here because of the identification of land use in the same vegetation growing season, which was associated with a smaller error in the delineation of the analyzed areas. For the selection of the year (2011) of the RapiEye images, the most temporally distant and available imagery for all the studied metropolitan areas in the same month was considered, and the year 2016 or 2017 was due to the timing of the start of the ongoing study.

The decision to use Landsat imagery was due to their 40-year uninterrupted sequence of observations and its available access [Bauer et al. 2003, Vogelmann et al. 2016]. The principle was adopted that the recording month (August) would be the same in all images and all time periods (i.e., 1996/97, 2011, 2016/17), cloudiness for a single scene no more than 20%, radiometric resolution: eight bits; spectral resolution: minimum four channels. All images were acquired in June 2018. These images were pre-processed and then analysed.

Also, in case of the RapidEye multispectral satellite images, which is characterized by a constellation of five satellites, placed in a heliosynchronous orbit moving at 19-minute intervals, showing in 5 spectral channels (RGB + 2xNIR) with spatial resolution equal to 5.0 m [Krischke et al. 2000, Oliveira Duarte et al. 2016] the recording month was August. Use of images not from one year, but from two years (2016 or 2017) was caused by the necessity to select the best photos for all surveyed objects (metropolitan areas) - photos without cloud cover for all analysed municipalities of selected metropolitan areas.

3.2. Characteristics of selected objects

In the project 2016/21/D/HS4/00264 Urban agriculture as a challenge to the sustainable development of metropolitan areas in Poland-economic, social, environmental and planning aspects, under which the described research was carried out, the analyses were carried out on cities (MA cores) and selected municipalities located in the 4 largest (polycentric) Polish metropolitan areas: Warsaw (MA1), Krakow (MA2), Tri-City (MA3) and Wroclaw (MA4). The first of them, i.e., Warsaw MA, is the only Polish metropolitan area with a core of over 1.7 million inhabitants. As the capital of Poland, it is also characterized by the highest population density, higher wages, and higher dynamics of migration processes. The remaining cores of metropolitan areas are inhabited by 640 to 771 thousand people and present similar socio-economic characteristics. Distribution of the discussed metropolitan areas in Poland is shown in Figure 1.



Source: Author's own study

Fig. 1. Distribution of research objects in the territory of Poland

Table 1. Municipalities selected for research

Metropolitan area (MA)	Core (MA)	Bordering on the MA core		Located farther from the MA core	
		Communes with favourable farmland biophysical parameters	Communes with unfavourable farmland biophysical parameters	Communes with favourable farmland biophysical parameters	Communes with unfavourable farmland biophysical parameters
Warsaw (MA1)	Powsinek area	Michalowice	Stare Babice	Teresin	Radziejowice
Krakow (MA2)	os. Wyciaze	Igolomia-Wawrzenczyce	Wieliczka	Proszowice	Tokarnia
Tri-City (MA3)	Gdansk os. Komary	Stegna	Kosakowo	Nowy Dwor Gdanski	Suleczyno
Wroclaw (MA4)	os. Wojszyce	Kobierzyce	Czernice	Sobotka	Prusice

In each metropolitan area, the research was conducted in a deliberately selected housing estate of the core of the metropolitan area (at least 1 housing estate) and two municipalities located directly at the border of cities and two located on the outskirts of metropolitan areas. In addition, it was assumed that one of the municipalities located at the border of the MA core would have very good farmland biophysical vegetation parameters, and the other one – poor. The same assumption applied to municipalities located further from the core of metropolitan areas.

The selection of municipalities located in different metropolitan areas was resulted from the need to consider large diversity of individual parts of the country, but above all to verify whether, with different external conditions (differences in the level of agricultural development, diversified agrarian structure, etc.), the location in relation to the core and farmland biophysical parameters in the same way affect LULCCs.

For each of the selected municipalities (Table 1) assessed were condition and changes (years 1996–2017) of the structure of land use (forests, agricultural land, grassland, wasteland, water), also the subject of analysis was expansion of buildings (buildings compact and dispersed) to agricultural lands.

3.3. Processing of remote sensing images

Based on the acquired images, colour compositions were made and then subjected to digital classification. The following colour compositions were created for the LANDSAT images: Warsaw MA – (143), Krakow MA – (412), Tri-City MA – (452), Wroclaw MA – (412), which reflected the utility structure data in the best way.

For RapidEye images, colour compositions were made based on the following channels:

- Warsaw MA – (245) for 2011, and (412) for 2017,
- Krakow MA – (123) for 2011, and (531) for 2017,
- Tri-City MA – (123) for 2011, and (423) for 2016,
- Wroclaw MA – (123) for 2011, and (435) for 2016.

For the comprehensive analysis presented in the study, the classification supervised with the 'Maximum Likelihood' technique was applied. The use of this method was described by Sandau et al. [2010], Vogelmann et al. [2016], Li and Yeh [1998] after: Lu et al. [2004] applied supervised classification by the maximum likelihood method to detect land cover changes in the Pearl River Delta in China.

In the first phase, supervised classification consists in selecting the so-called training fields on the basis of which the patterns of classes are created, i.e., similar to measures and ranges of classes in the unsupervised method. Detailed image statistics are calculated for training fields (e.g., DN values: average, minimum, maximum, standard deviation, variance). In the next step, pixels are assigned to user-defined classes (e.g., forest, water, buildings) using various classification algorithms. This process is called supervised classification because the user has full control over the entire process. The last stage is analysis of the credibility of the classification, which is carried out using similar to training fields, but designated independently of them, set of test fields (also called control plots) [Hejmanowska and Wężyk 2020].

Maximum Likelihood Classification, MLC – is a method based on calculating the probability of each pixel belonging to a specific class. The pixel is assigned to the class with the highest probability. The method assumes that the pattern statistics used to calculate the probability value of belonging to a given class present normal distribution.

As indicated, the 'Maximum Likelihood' technique was selected for the classification of the research areas in question and its accuracy was assessed.

Supervised classification of all images was carried out by the same person, at different time periods (for different metropolitan areas), in SAGA GIS software. The sampling process was done manually and a minimum of 20 samples were selected for each of the adopted land classes. From the classifiers tested, the maximum likelihood method was selected providing the most accurate results compared to the parallel, least distance or Mahalanobis distance methods.

When selecting training fields that reflect the individual classes, particular attention was paid to accuracy when selecting pixels. As a result of the classification, 7 classes of land cover and land use were obtained for three research dates (1999, 2011 and 2016–2017), i.e., arable land, grassland, urbanized areas (compact and distributed housing), water, forests, and wasteland. Effects of the study are presented on the land use maps for individual research dates and metropolitan areas.

The accuracy of the classification depends, among others, on the selection of training fields, which affects the quality of patterns in individual classes. The correctness of these patterns can be checked using scatter plots. On both axes, the brightness values in two spectral channels are presented, and the graph presents the spread and frequency of pixels from individual training fields. When the ranges of individual classes overlap, a lower accuracy of classification can be expected [Hejmanowska and Wężyk 2020].

Traditional analysis of the accuracy of classification result uses a confusion matrix.

This matrix compares the classification results with the land cover data that can be considered error-free (test fields).

The test fields should:

- be selected very carefully – if possible, supported by information from field interview, analysis of accurate maps or satellite images of higher resolution from the same period of time,
- be evenly distributed over the areas of land cover classes – be representative for a given class of field features,
- be outside the training areas previously used for the classification.

Based on the confusion matrix, it is possible to determine parameters describing the accuracy of the classification:

- Overall accuracy, which is defined as the ratio of the number of pixels classified correctly (sum of the elements on the diagonal) to the number of pixels that were included in the accuracy assessment (sum of elements in the verification fields).

Accuracy of the classification is within the confidence interval depending on the number of verifications pixels.

- Kappa coefficient, which describes total error of classification and degree of compatibility between the compared images. It takes the value 0–1, where 1 is a full match, and 0 – a match at the level that would result from randomly distributing data.
- Producer's accuracy, also called simply 'accuracy', which is defined for each class as the ratio of correctly classified pixels of a given class (value on the diagonal) to the sum of all pixels of that class in the verification fields (line sum).
- User's accuracy, also known as 'reliability' – it is defined for each class as the ratio of correctly classified pixels of a given class (value on the diagonal) to the number of all pixels of a given class obtained as a result of the classification (sum of columns).

The quality control of supervised classification showed accuracy of 89.3% for LANDSAT 5 TM scene analyses and 91.8% for RapidEye images. Kappa coefficient for the discussed classification was: 0.84 (LANDSAT TM) and 0.89 (RapidEye).

4. Research results and discussion

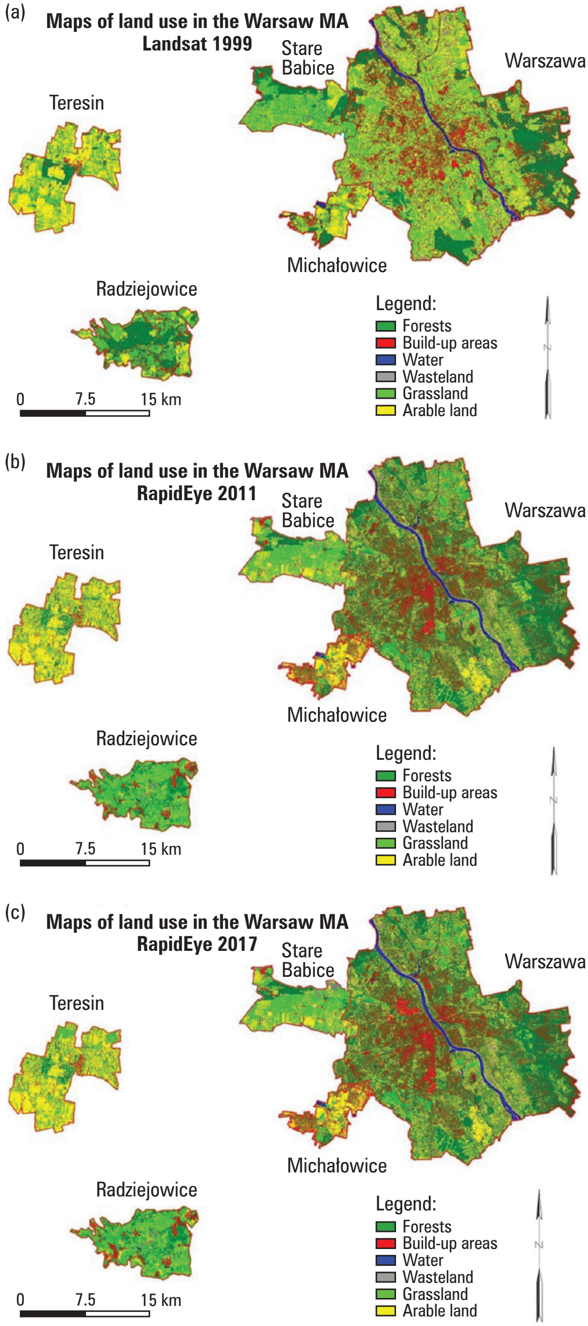
The basic assumption in the adopted method of examining changes was to perform independent classification of satellite images for each registration date, using the same set of land cover classes and to compare classification images. Accuracy of distinguishing individual land cover classes directly affects the precision of determining change areas. Therefore, it is extremely important to use such a classification method that would ensure classification of the satellite image with the highest possible accuracy. In the presented study it was the method of the highest probability [Kwoczyńska et al. 2019].

The research results were presented using the graphical (compilation of numerical maps), tabular (statistical summaries) and descriptive methods. The project was based on remote sensing data: RapidEye and LANDSAT TM satellite images.

The obtained results, land use maps in individual MAs, are presented in Figure 2a–c for the Warsaw MA, Figure 3a–c for the Krakow MA, Figure 4a–c for the Tri-City MA and Figure 5a–c for the Wroclaw MA.

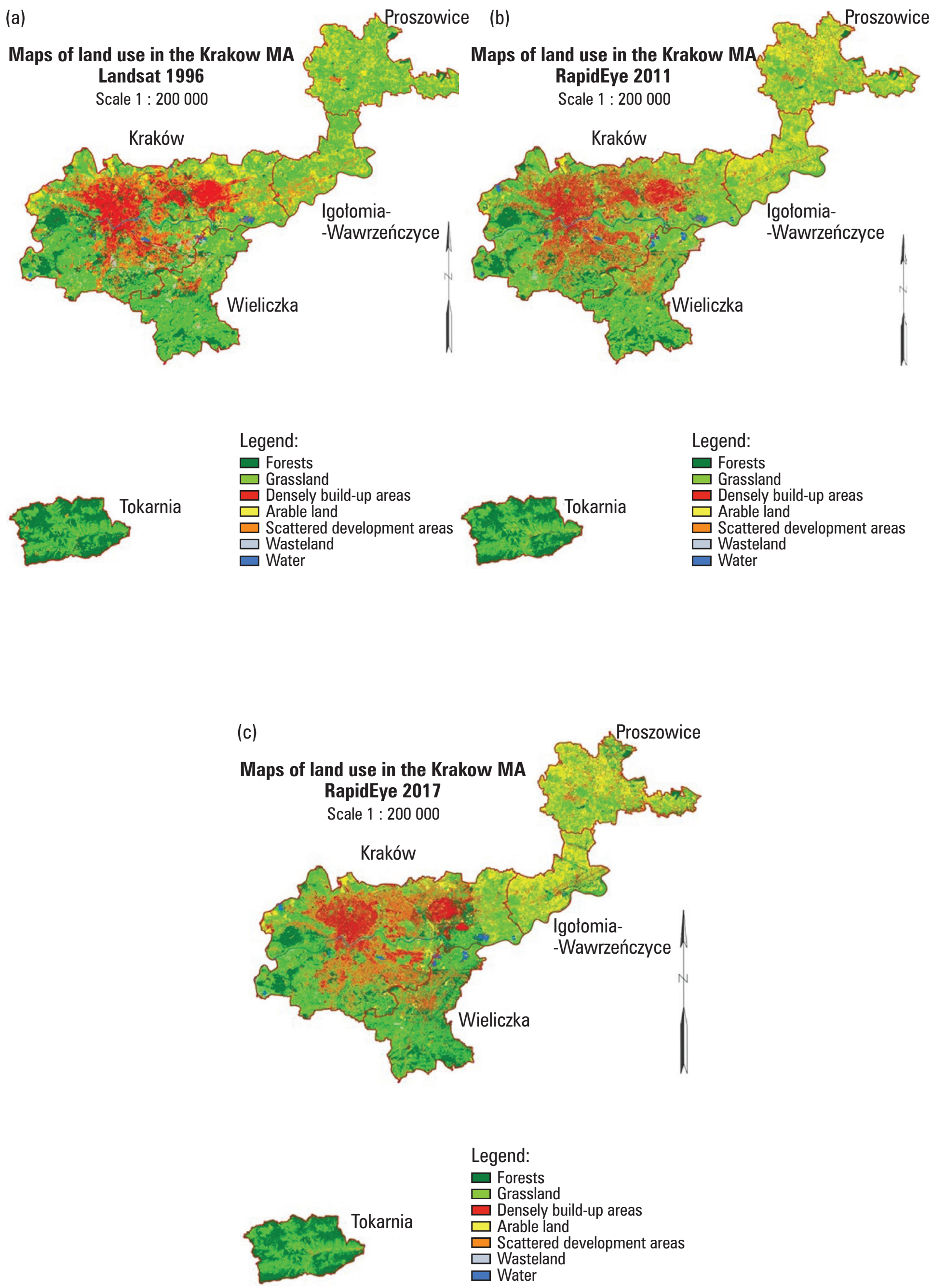
Comparison of the obtained Land Use Land Cover (LULC) maps of the studied areas from individual time periods, allowed to determine changes in the structure of land use both in the metropolis and its neighbouring communes over a period of 20 years. A detailed list of the percentages of individual land classes (LULC) within of the studied metropolitan areas is presented in Tables 2–4.

Changes in land use that took places for all metropolitan areas between individual research periods, and in total over 20 years, are presented in Tables 5–7. Losses of land, i.e., their reduction between individual years, are marked in red. The recorded increase in the area of built-up land has most often taken place at the expense of arable land and grassland or forests.



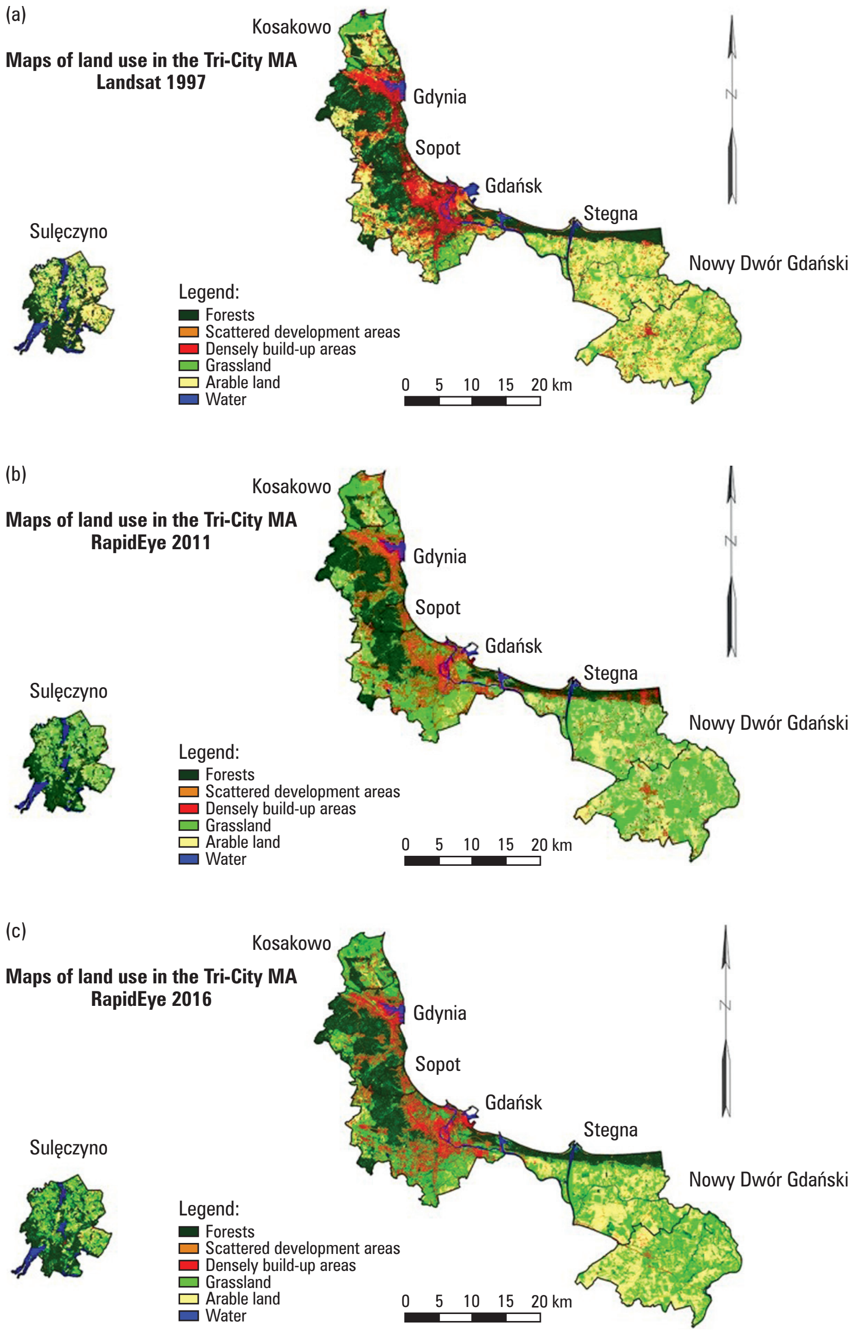
Source: Author's own study

Fig. 2. Maps of land use in the Warsaw MA (MA1) prepared on the basis of the following images: (a) Landsat from 1999, (b) RapidEye from 2011, (c) RapidEye from 2017



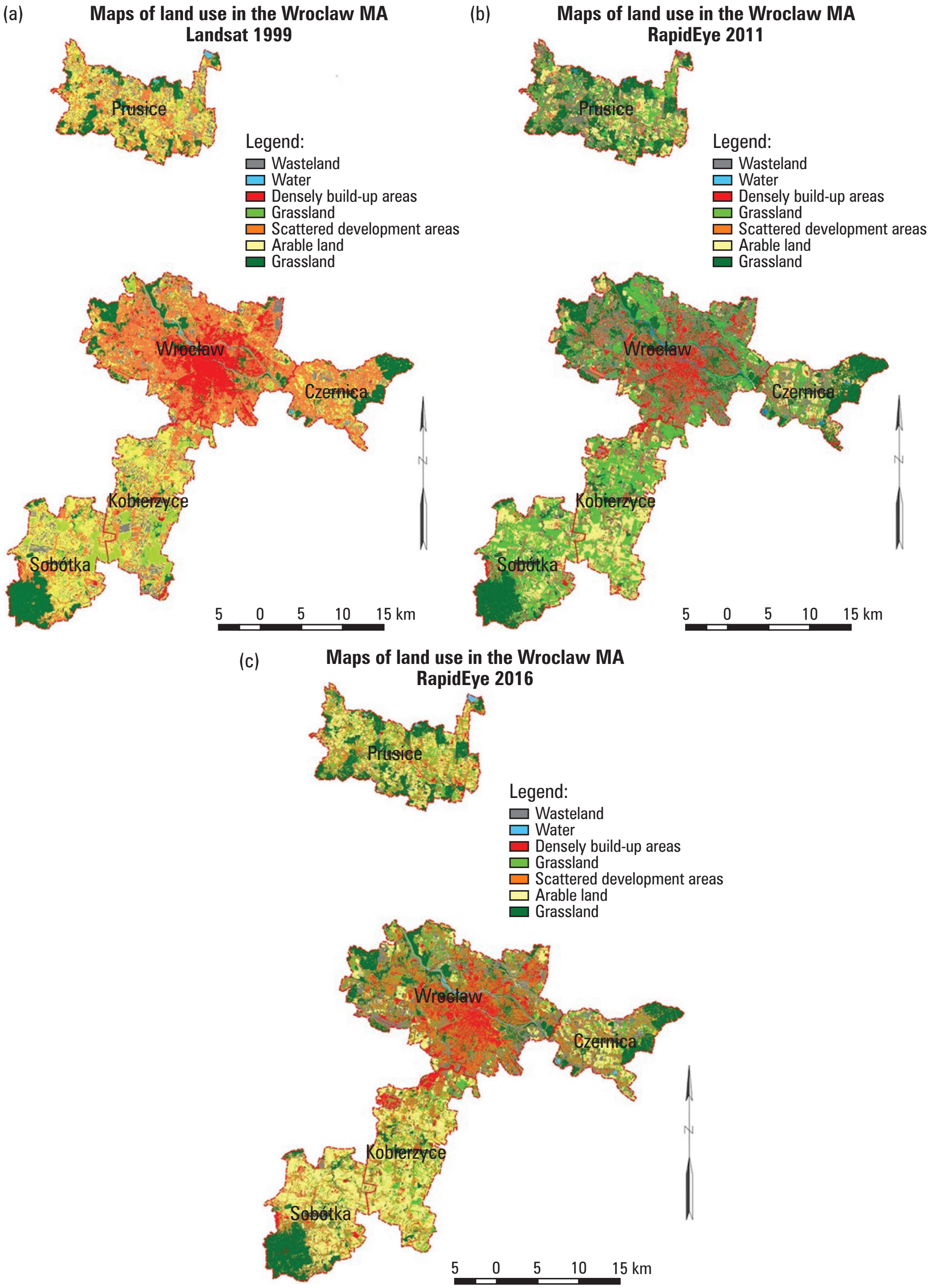
Source: Author's own study

Fig. 3. Maps of land use in the Krakow MA (MA2) prepared on the basis of the following images: (a) Landsat from 1996, (b) RapidEye from 2011, (c) RapidEye from 2017



Source: Author's own study

Fig. 4. Maps of land use in the Tri-City MA (MA3) prepared on the basis of the following images: (a) Landsat from 1997, (b) RapidEye from 2011, (c) RapidEye from 2016



Source: Author's own study

Fig. 5. Maps of land use in the Wroclaw MA (MA4) prepared on the basis of the following images: (a) Landsat from 1999, (b) RapidEye from 2011, (c) RapidEye from 2016

Table 2. Percentage summary of individual land classes (LULC) in each commune of the studied metropolitan areas made on the basis of Landsat images

LULC		Landsat images 1996/97					
		Forests [%]	Grassland [%]	Arable land [%]	Buildings [%]	Water [%]	Wasteland [%]
Warsaw MA (MA1)	Warsaw	26.70	23.60	22.10	14.10	1.80	12.00
	gm. Michalowice	2.70	26.40	43.30	25.00	1.60	1.00
	gm. Stare Babice	15.20	32.30	17.40	7.80	0.00	27.20
	gm. Teresin	4.40	35.50	55.90	4.10	0.00	0.10
	gm. Radziejowice	23.50	31.20	12.10	13.90	0.60	18.80
Krakow MA (MA2)	Krakow	6.27	28.69	22.28	29.84	3.33	9.59
	gm. Igolomia- -Wawrzenczyce	0.90	41.21	33.02	17.56	3.92	3.39
	gm. Wieliczka	19.76	38.13	11.79	16.00	5.09	9.24
	gm. Proszowice	3.39	39.25	33.00	13.30	1.25	9.80
	gm. Tokarnia	37.42	20.92	3.14	4.17	2.64	0.50
Tri-City MA (MA3)	Gdansk	29.00	14.00	20.00	32.00	5.00	0.00
	Sopot	69.00	8.00	4.00	19.00	0.00	0.00
	Gdynia	53.00	8.00	11.00	25.00	3.00	0.00
	gm. Stegna	14.00	17.0	55.00	12.00	2.00	0.00
	gm. Kosakowo	26.00	19.00	36.00	18.00	1.00	0.00
	gm. Nowy Dwor Gdanski	7.00	23.00	60.00	10.00	0.00	0.00
	gm. Suleczyno	41.00	8.00	36.00	6.00	9.00	0.00
Wroclaw MA (MA4)	Wrocław	10.00	2.00	9.00	72.00	2.00	5.00
	gm. Kobierzyce	4.00	18.00	38.00	24.00	0.00	15.00
	gm. Czernice	20.00	2.00	19.00	52.00	1.00	6.00
	gm. Sobotka	22.00	13.00	37.00	20.00	0.00	8.00
	gm. Prusice	17.00	4.00	36.00	30.00	1.00	12.00

Table 3. Percentage summary of individual land classes (LULC) in each commune of the studied metropolitan areas made on the basis of RapidEye images from 2011

LULC		RapidEye images from 2011					
		Forests [%]	Grassland [%]	Arable land [%]	Buildings [%]	Water [%]	Wasteland [%]
Warsaw MA	Warsaw	39.40	14.80	19.10	14.70	2.30	9.70
	gm. Michalowice	2.70	20.70	37.40	36.30	1.70	1.30
	gm. Stare Babice	0.00	20.50	20.40	12.00	0.00	35.40
	gm. Teresin	0.00	37.50	53.50	4.30	0.00	0.10
	gm. Radziejowice	0.90	36.40	9.60	19.30	0.90	13.80
Krakow MA (MA2)	Krakow	5.41	20.37	19.40	41.66	3.11	10.04
	gm. Igolomia--Wawrzenczyce	0.84	37.87	35.40	19.63	3.80	2.46
	gm. Wieliczka	19.20	35.54	10.03	21.26	5.23	8.73
	gm. Proszowice	2.87	36.59	36.19	16.70	1.22	6.43
	gm. Tokarnia	55.30	27.22	4.43	8.32	3.54	1.20
Tri-City MA (MA3)	Gdansk	23.00	22.00	17.00	34.00	4.00	0.00
	Sopot	64.00	10.00	3.00	23.00	0.00	0.00
	Gdynia	52.00	11.00	8.00	26.00	3.00	0.00
	gm. Stegna	14.00	27.00	45.00	12.00	2.00	0.00
	gm. Kosakowo	24.00	34.00	23.00	19.00	0.00	0.00
	gm. Nowy Dwor Gdanski	6.00	33.00	49.00	12.00	0.00	0.00
	gm. Suleczyno	44.00	19.00	21.00	8.00	8.00	0.00
Wroclaw MA (MA4)	Wroclaw	19.00	12.00	6.00	28.00	1.00	34.00
	gm. Kobierzyce	4.00	27.00	34.00	16.00	0.00	18.00
	gm. Czernice	31.00	10.00	19.00	14.00	2.00	24.00
	gm. Sobotka	21.00	20.00	29.00	14.00	0.00	16.00
	gm. Prusice	24.00	6.00	38.00	16.00	1.00	15.00

Table 4. Percentage summary of individual land classes (LULC) in each commune of the studied metropolitan areas made on the basis of RapidEye images from 2016/17

LULC		RapidEye images from 2016/17					
		Forests [%]	Grassland [%]	Arable land [%]	Buildings [%]	Water [%]	Wasteland [%]
Warsaw MA (MA1)	Warsaw	41.20	12.10	18.00	17.00	2.30	9.40
	gm. Michalowice	2.70	19.80	34.80	39.50	1.70	1.40
	gm. Stare Babice	11.50	22.10	20.30	12.30	0.00	33.70
	gm. Teresin	5.50	36.80	53.00	4.60	0.00	0.10
	gm. Radziejowice	17.40	35.90	8.90	19.90	0.90	17.00
Krakow MA (MA2)	Krakow	5.04	20.23	18.40	47.22	2.82	6.29
	gm. Igolomia--Wawrzenczyce	0.84	37.71	37.00	20.15	3.61	0.69
	gm. Wieliczka	18.21	34.41	10.00	23.33	5.13	8.92
	gm. Proszowice	2.90	35.12	35.01	17.22	1.10	8.65
	gm. Tokarnia	53.91	26.32	4.44	8.76	3.44	3.13
Tri-City MA (MA3)	Gdansk	22.00	28.00	11.00	36.00	3.00	0.00
	Sopot	63.00	11.00	3.00	23.00	0.00	0.00
	Gdynia	53.00	14.00	4.00	27.00	2.00	0.00
	gm. Stegna	15.00	28.00	41.00	14.00	2.00	0.00
	gm. Kosakowo	22.00	47.00	10.00	21.00	0.00	0.00
	gm. Nowy Dwor Gdanski	5.00	36.00	46.00	13.00	0.00	0.00
	gm. Suleczyno	45.00	26.00	10.00	8.00	7.00	0.00
Wroclaw MA (MA4)	Wroclaw	19.00	10.00	5.00	35.00	0.00	30.00
	gm. Kobierzyce	4.00	16.00	45.00	22.00	0.00	13.00
	gm. Czernice	21.00	7.00	21.00	22.00	2.00	27.00
	gm. Sobotka	23.00	3.00	46.00	19.00	0.00	9.00
	gm. Prusice	22.00	5.00	41.00	23.00	1.00	10.00

Table 5. Percentage summary of changes in land use (LULC) of the studied metropolitan areas for individual communes based on Landsat 1997 – RapidEye 2011

LULC		Landsat – RapidEye 2011					
		Forests [%]	Grassland [%]	Arable land [%]	Buildings [%]	Water [%]	Wasteland [%]
Warsaw MA (MA1)	Warsaw	13.10	–9.00	–3.00	0.60	0.50	–2.30
	gm. Michalowice	0.00	–5.70	–5.90	11.30	0.10	0.20
	gm. Stare Babice	–3.50	–11.70	2.90	4.10	0.00	8.20
	gm. Teresin	0.20	2.00	–2.30	0.10	0.00	0.00
	gm. Radziejowice	–3.60	5.20	–2.50	5.50	0.40	–5.00
Krakow MA (MA2)	Krakow	–0.86	–8.33	–2.87	11.83	–0.23	0.45
	gm. Igolomia--Wawrzenczyce	–0.06	–3.34	2.39	2.07	–0.12	–0.93
	gm. Wieliczka	–0.56	–2.58	–1.76	5.27	0.14	–0.51
	gm. Proszowice	–0.52	–2.67	3.19	3.40	–0.03	–3.37
	gm. Tokarnia	0.84	–3.16	–0.14	2.27	–0.29	0.47
Tri-City MA (MA3)	Gdansk	–6.00	8.00	–3.00	2.00	–1.00	0.00
	Sopot	–5.00	2.00	–1.00	4.00	0.00	0.00
	Gdynia	–1.00	3.00	–3.00	1.00	0.00	0.00
	gm. Stegna	0.00	10.00	–10.00	0.00	0.00	0.00
	gm. Kosakowo	–2.00	15.00	–13.00	1.00	–1.00	0.00
	gm. Nowy Dwor Gdanski	–1.00	10.00	–11.00	2.00	0.00	0.00
	gm. Suleczyno	3.00	11.00	–15.00	2.00	–1.00	0.00
Wroclaw MA (MA4)	Wroclaw	9.00	10.00	–3.00	–44.00	–1.00	29.00
	gm. Kobierzyce	0.00	9.00	–4.00	–8.00	0.00	3.00
	gm. Czernice	11.00	8.00	0.00	–38.00	1.00	18.00
	gm. Sobotka	–1.00	7.00	–8.00	–6.00	0.00	8.00
	gm. Prusice	7.00	2.00	2.00	–14.00	0.00	3.00

Table 6. Percentage summary of changes in land use (LULC) of the studied metropolitan areas for individual communes based on RapidEye 2011 and RapidEye 2017 images

LULC		RapidEye 2011 – RapidEye 2016/17					
		Forests [%]	Grassland [%]	Arable land [%]	Buildings [%]	Water [%]	Wasteland [%]
Warsaw MA	Warsaw	1.90	−2.80	−1.10	2.30	0.00	−0.30
	gm. Michalowice	0.10	−0.80	−2.70	3.20	0.00	0.20
	gm. Stare Babice	−0.20	1.60	0.00	0.30	0.00	−1.70
	gm. Teresin	0.90	0.60	−0.60	0.30	0.00	0.00
	gm. Radziejowice	−2.50	−0.50	−0.70	0.50	0.00	3.20
Krakow MA	Krakow	−0.38	−0.14	−1.00	5.56	−0.28	−3.76
	gm. Igolomia--Wawrzenczyce	0.00	−0.16	1.59	0.53	−0.18	−1.78
	gm. Wieliczka	−0.99	−1.13	−0.03	2.07	−0.10	0.18
	gm. Proszowice	0.03	−1.46	−1.18	0.51	−0.12	2.22
	gm. Tokarnia	−1.38	−0.90	0.01	0.44	−0.10	1.93
Tri-City MA	Gdansk	−1.00	6.00	−6.00	2.00	−1.00	0.00
	Sopot	−1.00	1.00	0.00	0.00	0.00	0.00
	Gdynia	1.00	3.00	−4.00	1.00	−1.00	0.00
	gm. Stegna	1.00	1.00	−4.00	2.00	0.00	0.00
	gm. Kosakowo	−2.00	13.00	−13.00	2.00	0.00	0.00
	gm. Nowy Dwor Gdanski	−1.00	3.00	−3.00	1.00	0.00	0.00
	gm. Suleczyno	1.00	7.00	−7.00	0.00	−1.00	0.00
Wroclaw MA	Wrocław	0.00	−2.00	−1.00	7.00	0.00	−4.00
	gm. Kobierzyce	0.00	−11.00	11.00	6.00	0.00	−6.00
	gm. Czernice	−10.00	−3.00	2.00	8.00	0.00	3.00
	gm. Sobotka	2.00	−16.00	17.00	5.00	0.00	−7.00
	gm. Prusice	−2.00	−2.00	3.00	7.00	0.00	−6.00

Table 7. Percentage summary of changes in land use (LULC) of the studied metropolitan areas for individual communes based on Landsat 1997 – RapidEye 2017 images

LULC		Landsat 1996/97 – RapidEye 2016/17					
		Forests [%]	Grassland [%]	Arable land [%]	Buildings [%]	Water [%]	Wasteland [%]
Warsaw MA	Warsaw	15.00	−11.70	−4.10	2.90	0.50	−2.60
	gm. Michalowice	0.00	−6.50	−8.50	14.50	0.10	0.40
	gm. Stare Babice	−3.70	−10.20	2.90	4.50	0.00	6.50
	gm. Teresin	1.10	1.30	−2.90	0.50	0.00	0.00
	gm. Radziejowice	−6.10	4.70	−3.20	6.00	0.40	−1.80
Krakow MA	Krakow	−1.24	−8.46	−3.88	17.39	−0.51	−3.30
	gm. Igolomia--Wawrzenczyce	−0.06	−3.50	3.98	2.59	−0.31	−2.70
	gm. Wieliczka	−1.55	−3.72	−1.78	7.34	0.04	−0.32
	gm. Proszowice	−0.49	−4.13	2.01	3.92	−0.15	−1.15
	gm. Tokarnia	−0.54	−4.06	−0.13	2.72	−0.39	2.40
Tri-City MA	Gdansk	−7.00	14.00	−9.00	4.00	−2.00	0.00
	Sopot	−6.00	3.00	−1.00	4.00	0.00	0.00
	Gdynia	0.00	6.00	−7.00	2.00	−1.00	0.00
	gm. Stegna	1.00	11.00	−14.00	2.00	0.00	0.00
	gm. Kosakowo	−4.00	28.00	−26.00	3.00	−1.00	0.00
	gm. Nowy Dwor Gdanski	−2.00	13.00	−14.00	3.00	0.00	0.00
	gm. Suleczyno	4.00	18.00	−22.00	2.00	−2.00	0.00
Wroclaw MA	Wroclaw	9.00	8.00	−4.00	−37.00	−1.00	25.00
	gm. Kobierzyce	0.00	−2.00	7.00	−2.00	0.00	−3.00
	gm. Czernice	2.00	5.00	2.00	−30.00	1.00	20.00
	gm. Sobotka	1.00	−10.00	9.00	−1.00	0.00	1.00
	gm. Prusice	5.00	1.00	5.00	−7.00	0.00	−4.00

The analysis showed that in the studied metropolitan areas the greatest changes took place in communes with poor farmland biophysical parameters. For those communes, observed was even a few points decrease in the area of arable land and grassland in favour of built-up areas, but it should also be noted that there have been changes in arable land in favour of grassland, which may also indicate the conversion of land to grassland for later set-aside.

In the Warsaw MA, there have been changes to grassland, arable land, and in communes with poor farmland biophysical parameters, also forests, all to the benefit of built-up areas. But even in a commune with good farmland biophysical parameters (commune of Michalowice), an increase in built-up areas at the expense of grassland and arable land was observed. In Warsaw itself, arable land and grassland were replaced by forests, the area of which increased by 15%.

In the case of Krakow even in the city core, there was a significant loss of grassland, as well as wasteland, which were turned into built-up areas. These problems are described by Grădinaru S.R. [2015]. In communes with good farmland biophysical parameters grassland has turned into arable land (which may be due to the fact that animal breeding was abandoned, so land that was productive was converted into arable land) and partially into built-up land. Over the course of 20 years, the area of forest land and grasslands in the Krakow metropolis and its vicinity has decreased by almost 10% in total. For arable land, their decrease by almost 4% was recorded, and the wastelands decreased by almost 7.5% (in total for the entire MA), which may result from their transformation into built-up areas, as these recorded the greatest increase, i.e., by over 17%, which is described by [Grădinaru et al. 2015].

The changes that took place in the Tri-City are of completely different nature, because it is a metropolis where, apart from the shipbuilding industry, tourism is very well developed, and the structure of utilised agricultural area differs from that in other MAs (very large farms prevail there). In the case of this metropolitan area (MA), compared to other MAs, no wasteland appears in the analyses. Here, too, the biggest changes took place in communes with poor farmland biophysical parameters. Arable land was transformed into grassland and areas with distributed housing. In Gdansk, Sopot, and Gdynia, belonging to the Tri-City, the greatest changes over 20 years took place in arable land, which in total decreased by 17%, and forest land (by 13% in total). All this in favour of grassland (increased by 23%) and built-up areas, which increased in total in all three cities by 10%.

In metropolitan area of Wroclaw, over 20 years, area of forests and arable land in-creased in the entire MA by 17% and 19%, respectively. It came at the expense of grassland and, to a large extent, distributed housing. In communes with good farmland bio-physical parameters grassland has turned into arable land. This is described by Sroka and Zmija [2021], where authors draw attention to elimination of livestock production, and thus the elimination of grassland and its conversion into arable land. In the metropolis itself, i.e., Wroclaw, there was an increase in the area of forests, grassland, and wasteland, but the latter were most likely intended for built-up areas, mainly at the expense of distributed housing.

Summing up the changes of land use that took place in the Polish metropolitan areas under consideration, considering the importance of natural conditions, a large loss of arable land was noticed in communes with worse natural conditions, and slightly smaller changes in communes with good farmland biophysical parameters. Arable lands are also being transformed in areas with very good natural conditions, but to a lesser extent.

This relationship is consistent with the operation of the law of economic rents (differential rent I). Also, in the literature on the subject it is emphasized that the land with lower suitability for agricultural production is excluded from agricultural use in the first place [Gellrich and Zimmermann 2007, Xie et al. 2014, Wojewodzic 2017]. The research also showed very big changes in the area of grassland, and they were strongly correlated with changes in arable land. Increase of the grassland area took place at the expense of arable land.

In most of the analysed metropolitan areas, the more intensive production on arable land was transformed into a less intensive one – based on the use of grassland. Other researchers (e.g. Wojewodzic 2012, Wästfelt and Zhang 2016, Pölling et al. 2017) note that in areas with a relatively attractive labour market (e.g., suburban communes), some farm owners, especially part-time farmers, give up farming and start work outside agriculture.

The observed trends contradict the operation of 'classic' economic rents, as land is not converted to other, more profitable, uses. So, what are the factors that encourage land users to take seemingly unreasonable actions? The answer to this question is provided by the new institutional economics and the theory of rent-seeking [Musiał and Wojewodzic 2014, Satoła et al. 2018]. Users of agricultural land (including grassland), apart from income from production activities, may obtain other economic rents, including institutional rents (payments under the CAP, taking advantage of insurance privileges), re-zoning fee (conversion of agricultural to construction land) and location rents (higher prices for land with a convenient location). Speculative actions are also of great importance. Sroka et al. [2017] conducting research on the problem of abandonment of agricultural land use notice that some owners of agricultural land do not sell or lease land waiting for a good purchase offer to the land and increase of its value in the future. Thus, extensification of agricultural activity can be beneficial to the land user [Kwoczyńska et al. 2019].

It is also worth noting that the changes in land use that have occurred in the studied communes depend on their location in relation to the MA core. In the case of the Warsaw MA, much greater changes in use took place in communes more distant from the MA core (Radziejowice) and with unfavourable farmland biophysical parameters than those directly adjacent to it. In the case of the Krakow, Wroclaw, and Tri-City MAs the situation is the opposite, i.e., in communes with unfavourable farmland biophysical parameters and more distant from the core, the changes are smaller than in those directly adjacent to it.

5. Summary and conclusions

The aim of the study was to diagnose the main trends of changes in land cover in selected metropolitan areas in Poland. The analyses focused mainly on the assessment of changes in the share of arable land and grassland. The conducted research showed that the biggest changes took place in the MA core. It is also confirmed that the strong pressure of non-agricultural sector in cities reduces the share of arable land mainly in communes located close to the city. However, it should be noted that the natural conditions of agricultural activity were of greater importance in the conversion of arable land. Larger losses of arable land were recorded in communes with worse conditions for agricultural activity.

The research also showed that among the analysed metropolitan areas, only in the Tri-City and related communes, arable land was primarily converted into grassland. In the Warsaw and Krakow MAs, a large part of them was supplied to built-up areas, and in the Wroclaw MA, the arable land increased at the expense of dispersed buildings.

Progressive reduction in the intensity of agricultural activity is typical for the fragmented agriculture areas and is particularly relevant in communes with an attractive labour market. Growing share of green land with a simultaneous decline in livestock production may, however, be a symptom of speculative activity. Owners of agricultural land are reluctant to sell or lease them, as having land relatively close to the city may bring benefits in the form of re-zoning fee or location rent [Kwoczyńska et al. 2019].

The different nature of changes in the studied metropolitan areas results primarily from their geographical location, as well as the size and nature of the metropolis itself (MA core).

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