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Soil sealing changes in selected functional urban areas in Poland in 2012–2018

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Abstract: Soil sealing is a threat to soil and its ecosystem services. One of the main drivers of soil sealing is land degradation resulting from the expansion of urban areas, where it leads to such problems as the growing risk of flooding and local inundations, urban heat islands, or water shortages. The article focuses on analyses and quantification of the general degree of soil sealing in 2012–2018 in eight functional urban areas (FUA) in Poland, taking into account their division into the urban core (UC) and the commuting zone (CZ). We used the high resolution layer imperviousness density (HRL IMD) data to quantify soil sealing as well as data on land cover and land use with different spatial resolutions, i.e. from the European Urban Atlas project (UA) and the National Database of Topographic Objects (BDOT10k) to quantify artificial surfaces. The research determined the spatial differentiation of UCs and CZs in terms of the degree of soil sealing. We further observed higher average growth of sealed land in CZs. Quantitative and spatial analyses determined the spatial patterns of soil sealing in the FUA in Poland. Soil sealing intensified from 2012 to 2018. The process should be expected to continue in the coming years in light of the continuous transformation of vegetated areas into artificial ones. The conclusions should be considered valuable for the implementation of the spatial policy concerning sustainable land use and soil protection in suburban areas.

Keywords: ekranic technosols, functional urban areas (FUA), National Database of Topographic Objects (BDOT), land use, Urban Atlas, urban soils

INTRODUCTION

Soil sealing is defined as the permanent covering of land with an impermeable artificial layer. Burghardt (2006) proposes four types of sealing: total sealing related to roads and buildings; partial sealing related to circulation, such as pavements or bicycle paths; subsurface sealing related to underground structures covered with a layer of soil, such as underground car parks; and vertical sealing due to walls in the ground. Sealing is counted among the most substantial threats to the soil and its ecosystem services as a form of soil degradation caused by the expansion of urban areas (Burghardt, 2006; Scalenghe and Marsan, 2009; Xiao *et al.*, 2013). It causes a multitude of repercussions (Scalenghe and Marsan, 2009; Kostecki and Greinert, 2019), including lower food security through a decline in fertile and agriculturally suitable land, restricting carbon sequestration in the soil and reducing groundwater availability (Tóth, 2012; Tóth *et al.*, 2022), disturbance of the upper soil potential for rainwater and snowmelt storage, which increases the risk of local flooding (Pistocchi *et al.*, 2015; Paliaga *et al.*, 2020), disturbance in nutrient cycling, microorganisms diversity and enzymatic activity in soil (Piotrowska-Długosz and Charzyński, 2015; Pereira, O'Riordan and Stevens, 2021), and acceleration of climate change by promoting heat islands (Fokaides *et al.*, 2016; Murata and Kawai, 2018). Two point three per cent of the total area of the European Union (EU) was sealed in 2006 (EEA, 2013; Stolte *et al.* (eds.), 2015), while for EU urban areas, it was more than half (Prokop, Jobstmann and Schonbauer, 2011). Urban areas are defined as land use and cover (LUC) type referred to as artificial surfaces, which are anthropogenic surfaces dominated by human impact and not used for agriculture. Artificial surfaces cover any artificial structures (buildings, roads, infrastructure, and other sealed and paved areas) and related unsealed and vegetated surfaces (EU, 2020). They also include sites where natural surfaces are replaced by mining, dump sites, or designed landscapes (such as urban parks or amusement parks). The dominant land use of artificial surfaces is residential housing, traffic, mineral extraction and dump sites, non-agricultural production, sports, recreation, and leisure (EU, 2020). Recent years saw a consolidation of the notion of functional urban areas (FUA) comprising a densely-populated city referred to as the urban core (UC) and its commuting zone (CZ), which is less densely populated. Boundaries of FUA are updated when new data on commuting, 1 km^2 population grid cells are obtained, as well as when the boundaries of local administrative units change. These 1 km^2 grid cells are plotted in relation to their neighbouring cells to identify cluster types (this is the same process that is used for the degree of urbanisation typology). The method for pinpointing the zones is detailed in Dijkstra, Poelman and Veneri (2019). Functional urban areas exhibit high population density and very developed non-agricultural sectors of the economy, which require a sufficient number of housing, industrial, and commercial buildings. The Copernicus Land Monitoring Service (CLMS) maps land use and cover (LUC) of FUA in the EU under the Urban Atlas (UA). FUA comprise 22.9% of the EU's territory, housing 75% of its population (Barbero-Sierra, Marques and Ruiz-Pérez, 2013; EEA, 2021). According to UA data, 58 FUA in Poland were inhibited by 21.406 mln people in 2018, which was about 56% of the total population of the country. Therefore, FUA are an important study area for investigating the trends and dynamics in spatial changes, particularly soil sealing.

The degree of soil sealing reflects the per cent ratio of totally sealed surface to the selected area where it is located. Hence, the degree of sealing can be determined relative to the total selected area or area of land cover classified as artificial surface. Artificial surfaces do not necessarily have to be identical to sealed surface and can include surfaces not covered by impermeable layers, such as home vegetation, or other vegetated surfaces between buildings (Smiraglia *et al.*, 2014). According to Naumann *et al.* (2019), in 2006–2012 the average level of soil sealing per area in core cities in Europe was approximately 30% in Wrocław (Poland), 35% in Vienna (Austria) and Regensburg (Germany), 25–27% in Cambridge (UK) and Stockholm (Sweden), 50% in Milan (Italy) and 53% in Nantes (France). Considering the increase in sealed areas in Europe and the need to prevent its repercussions, the European Environmental Agency (EEA) had "Guidelines on best practice to limit, mitigate or compensate soil sealing" drafted in 2012 (EEA, 2012). The "EU soil strategy for 2030" (EC, 2021) also intends to reach zero land take by 2050, limit soil sealing through the circular use of land, and include land take hierarch into urban green planning. National EU member state regulations include restrictions on soil sealing as well. For instance, the degree of soil sealing in Poland is regulated in local zoning plans, which include land development indicators, development intensity, and the minimum required share of vegetated area for construction plots.

Soil sealing data for the EU are collected and provided by the CLMS as high-resolution raster imperviousness high resolution layer (IHRL) for 2009, 2012, 2015, and 2018. Data on LUC and artificial surface size change are provided by the CLMS as UA for 2006, 2012, and 2018 (CLMS, 2023). In addition, national databases also gather LUC data. In Poland, LUC data are collected in the Database of Topographic Objects (BDOT10k). Each of the databases offers a different spatial resolution, so their suitability for identifying artificial surfaces varies.

The objective of the paper is to assess the general degree of soil sealing in selected FUA in Poland divided into two zones (UCs and CZs) using available soil sealing data for 2012 and 2018. It is done through a qualitative analysis of the degree of soil sealing in the FUA, UCs and CZs followed by the determination of artificial surface ratio in the zones. Results of the analysis are then investigated to determine trends in sealed soil area and structure of sealed soil mix found in very developed cities and their peri-urban areas. We further determine the ratio of totally sealed land (SL) to the area of artificial surfaces based on UA and BDOT10k data and characterized artificial surfaces by FUA zones. The results can help regional and local spatial planners to foster sustainable development of key urban areas in Poland.

MATERIALS AND METHODS

The study involved eight selected functional urban areas (FUA) in Poland totalling 27,514.29 km^2, which constitutes about 8.5% of the terrestrial territory of the country. The following FUA were selected for the study: Warsaw (PL01), Łódź (PL02), Kraków (PL03), Wrocław (PL04), Poznan (PL05), Gdańsk (PL06), Szczecin (PL07), and Katowice (PL10). They were analysed divided into UCs and CZs. The location of the investigated FUA and other FUA in Poland are shown in Figure 1.

The central cities of the analysed FUA (the FUA' UCs) belong to one of two tiers of cities according to the classification scheme by Sobala-Gwosdz (2023) considering services and functions. Warsaw is the capital metropolis (tier I), while the others are supra-regional metropolises (tier II). The area of the cities constitutes from 6% (Warsaw) to 30% (Katowice) of the FUA. The eight investigated FUA had about 54% of the population of all 58 Polish FUA in 2018, which was 30% of the entire population of Poland. Please note that the 58 FUA do not cover the whole territory of Poland. The population in the Polish FUA grew from 10.851 mln to 11.535 mln between 2012 and 2018. The sizes of the areas are summarised in Table 1.

The research employs data from a project dedicated to soil sealing monitoring in Europe (IHRL) available as an high resolution layer imperviousness density (HRL IMD) layer for 2012 (EEA, 2018) and 2018 (EEA, 2020a). On HRL IMD, the percentage of sealed surface is mapped at a spatial resolution of 10 m for 2018 data and 20 m for 2006, 2009, and 2015 data (CLMS, 2023). The resolution of aggregate raster is 100 m (EEA, 2018; EEA, 2020a). The percentages of artificial surfaces in the FUA and changes in the ratios were determined with LUC data from the UA for 2012 (EEA, 2016) and 2018 (EEA, 2020b) and the BDOT10k data at the last available resolution. The BDOT10k is a vector database on the spatial positions of topographic objects in Poland and their characteristics. The content and level of detail of the BDOT10k are the same as for a 1:10,000 topographic map (Rozporządzenie, 2021). The minimum mapping unit (MMU) for urban classes in the UA is 0.25 ha. The LUC classes that

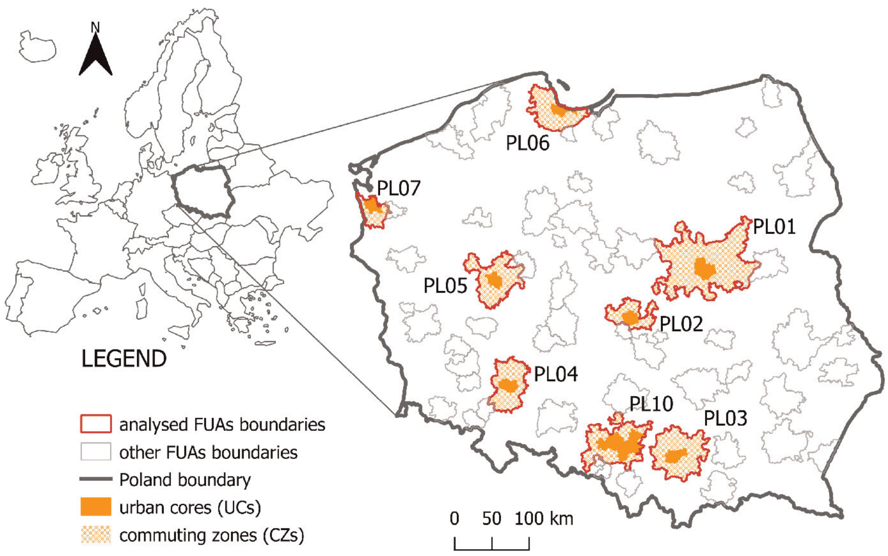

Fig. 1. Location of the investigated functional urban areas (FUA) in Poland divided into urban cores (UCs) and commuting zones (CZs); source: own elaboration based on EEA (2016) and https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/countries

Table 1. Functional urban areas (FUA), urban cores (UCs), and commuting zones (CZs) characteristics

Central city	FUA code	FUA size (km^2)	UC size (km^2)	CZ size (km^2)
Warsaw	PL01	8,614.64	517.23	8,097.41
Łódź	PL02	1,694.55	293.27	1,401.28
Kraków	PL03	3,757.74	326.80	3,430.94
Wrocław	PL04	2,648.10	292.82	2,355.28
Poznań	PL05	3,092.58	261.85	2,830.73
Gdańsk	PL06	2,632.22	261.70	2,370.52
Szczecin	PL07	1,128.91	300.54	8,28.387
Katowice	PL10	3,945.55	1,217.97	2,727.58

Source: own elaboration based on EEA (2016) and EEA (2020b).

constitute artificial surfaces according to the BDOT10k and UA employed here are listed in Table 2.

We converted the HRL IMD sealing raster data into a vector layer and clipped it to the outlines of the FUA. Then, the areas were divided into UCs and CZs along boundaries provided by the UA 2012 (EEA, 2016). The data were processed in QGIS v. 3.22.16. Area statistics were computed with the GRUPStats plugin for QGIS. We computed the percentage of sealed land (SL) in each FUA, UC, and CZ with Equation (1) based on the size of the area with mapped sealing (A_j) and using the degree of soil sealing (k):

$$SL = \sum_{i=1}^{100}\sum_{j=1}^{m} k_i A_j \tag{1}$$

where: k_i = the degree of soil sealing according to HRL IDM data (EEA, 2018; EEA, 2020a) in the assessment field ranging from i 1 to 100%; A_j = the size of the assessment field with the degree of soil sealing k_i according to HRL IDM data in assessment field m.

Table 2. Land use and cover (LUC) class according to the Urban Atlas (UA) and the National Database of Topographic Objects (BDOT10k) comprising artificial surface areas

Database	LUC classes
UA	continuous urban fabric (SL > 80%) (111); discontinuous urban fabric (SL 10–80%) (112); isolated structures (113); industrial, commercial, public, military, and private units (121); road and rail network and associated land (122); port areas (123); airports (124); mineral extraction and dump sites (131); construction sites (133); land without current use (134); green urban areas (141); sports and leisure facilities (142)
BDOT10k	multi-family housing (PTZB01); single-family housing (PTZB02); industrial and warehousing buildings (PTZB03); commercial buildings (PTZB04); other buildings (PTZB05); road area (PTKM01); railway area (PTKM02); road and railway area (PTKM03); airport road (PTKM04); square (PTPL01); municipal solid waste landfill (PTSO01); industrial waste landfill (PTSO02); land under technical facilities or structures (PTNZ01); industrial and warehousing land (PTNZ02)

Explanation: SL = sealed land.
Source: own elaboration.

With SL size, we were able to quantitatively juxtapose the years 2012 and 2018 despite different spatial resolutions of soil sealing data. We characterized the mix of sealed areas divided into its place of occurrence (UC or CZ), dividing SL by the degree of soil sealing (k) of the mapped area according to the HRL IDM data. To this end, we classified the calculated area of SL into five tiers depending on the degree of soil sealing (k) in the area where the SL was found: 1–20%, 21–40%, 41–60%, 61–80%, and 81–100%. With the UA and BDOT10k data, we determined the size of artificial surface areas in the FUA (AS_{FUA}), UCs (AS_{UC}) and CZs (AS_{CZ}). We then determined the percentage of AS_{FUA}, AS_{UC}, and AS_{CZ} in the analysed zones and quantified the sealed-land-to-artificial-surface ratio in individual zones of the FUA (AS_{FUA}, AS_{UC}, and AS_{CZ}).

RESULTS AND DISCUSSION

SOIL SEALING MIX IN THE FUA

According to the imperviousness density (IMD) data, area with 1 to 100% soil sealing in the selected functional urban areas (FUA) covered 2,629.59 km^2 in 2012 and 3,045.78 km^2 in 2018. Over the six years, the size of land with 1 to 100% sealing grew by 416.19 km^2 in total in the investigated area. The largest increase was found in the FUA of Warsaw (97.14 km^2) and Katowice (87.72 km^2) followed by 51 km^2 in the FUA of Kraków, Wrocław, and Poznań. Based on the degree of soil sealing determined for each field of assessment, we identified sealed land (SL) in the eight selected FUA, which amounted to 1,136.34 km^2 in 2012 and 1,410.81 km^2 in 2018. Hence, SL in the FUA grew by a total of 274.47 km^2 from 2012 to 2018. The share of SL in the FUA and their zones (urban cores (UCs) and commuting zones (CZs)) in 2012 and 2018 is shown in Table 3. As shown by Strand (2022) sealed surface estimated from high resolution layer imperviousness density (HRL IMD) can be 33% below the value estimated using high-resolution orthophotomap and the error is influenced by the spatial structure of the area, so errors may be smaller in urbanized regions.

The values of the degree of soil sealing (Tab. 3) demonstrate that soil sealing occurred mainly in UCs. The proportion of SL in UCs is estimated in the range from 12.78 to 26.28% for 2012. In 2018, it ranged from 14.99 to 27.03%. In CZs, it was from 1.64 to 3.39% in 2012 and from 2.50 to 4.27% of the CZ area in 2018. The mean increase in the degree of soil sealing in 2012–2018 was about 9.8% for UCs and about 39.9% for CZs. A positive trend in SL emerges from the data, more dynamic in CZs than in UCs. The area of SL in the FUA grew from 2012 to 2018 by 1% on average. The largest increase was in Katowice (1.28%) and the smallest in Szczecin (0.50%). Although the increase in sealing is similar across all the CZs, the increase in UCs varies.

This period saw a significant increase in 80–100% sealed areas in the FUA (Fig. 2). It is evident in Wrocław, Poznań, Gdańsk, and Szczecin, in UCs and CZs both. In UCs, intensified soil sealing was observed and transformation of areas with the degree of soil sealing at 20–60% into areas sealed in 80–100% for Warsaw, Łódź, Kraków and Katowice and transformation of areas with the degree of sealing at 40–80% into areas sealed in 80–100% for Wrocław, Poznań, Gdańsk and Szczecin (Fig. 2). The increase in the mix of areas with sealing degree at the level of 80–100% in Warsaw, Łódź, Kraków and Katowice was approximately 21%, while in the other cities it reached 16%. In CZs of Warsaw, Łódź, Wrocław and Katowice, the areas with the degree of sealing at 20–60% were transformed mainly into areas sealed in 80–100% (increase of ca. 13%), and less into areas sealed in 60–80% (increase of ca. 3%). Areas with sealing degree of 60–80% were transformed into sealed in 80–100% (increase of ca. 19%) for CZs of Poznań, Gdańsk and Szczecin. Specific changes happened in CZ of Kraków, where areas with soil sealing degree of 1–40% were converted into areas with sealing degree intervals of 40–60%, 60–80% and 80–100% (increase of ca. 7, 4 and 9% respectively). Moreover, both UCs and CZs exhibited an increase in sealing in zones 1–20%.

Peri-urban areas, or CZs today often have the same degree of development as urban areas but only half of them are as densely populated (Piorr, Ravetz and Tosics (eds.), 2011). In EU-27 and the UK regions, between 2012 and 2018, land take increased by 2.6 and 78% of it happened in CZs. Most land take i.e. 47%, took place in agricultural area (in which 36% was from pastures and 2.2% from permanent crops), 9% from forests and 1% from water and wetlands (EEA, 2021). Development of CZs leads to soil sealing, but the relatively greater availability of land for projects does not drive development intensification and sealing as much as in the case of UCs, where vacant land for development is not as readily available. It entails the replacement of the existing building with denser developments in UCs, while in CZs, vegetated areas are built up. Today, this phenomenon is caused by changes in social behaviour embodied in lifestyle changes and a new consumption structure rather than a growing population (EEA, 2006; Kudas, Wnęk and Tátošová, 2022). Additionally climbing land prices in cities promote projects in peri-urban areas, driving the growth of new transport networks. There is a trend for choosing to live in CZs, especially those that offer transport networks for accessing the city centre and using services and functions provided in the city, combined with less

Table 3. Degree of soil sealing in functional urban areas (FUA), urban cores (UCs), and commuting zones (CZs) and its changes in 2012–2018

Central city	FUA code	Degree of soil sealing (%) in the year						Changes in the degree of soil sealing in the study area in 2012–2018 (%)			Increase in the degree of soil sealing compared to 2012 (%)		
		2012			2018								
		FUA	UC	CZ	FUA	UC	CZ	FUA	UC	CZ	FUA	UC	CZ
Warsaw	PL01	3.22	20.77	2.09	4.15	24.02	2.88	0.94	3.25	0.79	29.12	15.63	37.66
Łódź	PL02	4.11	15.17	1.80	4.99	16.86	2.50	0.87	1.69	0.70	21.23	11.15	38.98
Kraków	PL03	2.85	15.13	1.68	3.80	17.95	2.45	0.95	2.82	0.78	33.56	18.65	46.37
Wrocław	PL04	3.65	19.74	1.64	4.72	20.95	2.70	1.07	1.22	1.06	29.47	6.17	64.23
Poznań	PL05	5.07	26.28	3.11	6.16	27.03	4.23	1.09	0.75	1.12	21.48	2.84	36.05
Gdańsk	PL06	5.14	20.95	3.39	6.07	22.42	4.27	0.94	1.47	0.88	18.27	7.02	25.95
Szczecin	PL07	5.74	16.26	1.92	6.24	16.16	2.64	0.50	-0.10	0.72	8.75	-0.60	37.51
Katowice	PL10	5.81	12.78	2.70	7.10	14.99	3.57	1.28	2.21	0.87	22.07	17.31	32.14
Mean		4.45	18.38	2.29	5.40	20.05	3.16	0.96	1.66	0.86	22.99	9.77	39.86

Source: own elaboration based on high resolution layer imperviousness density (HRL IDM) data (EEA, 2018; EEA, 2020a).

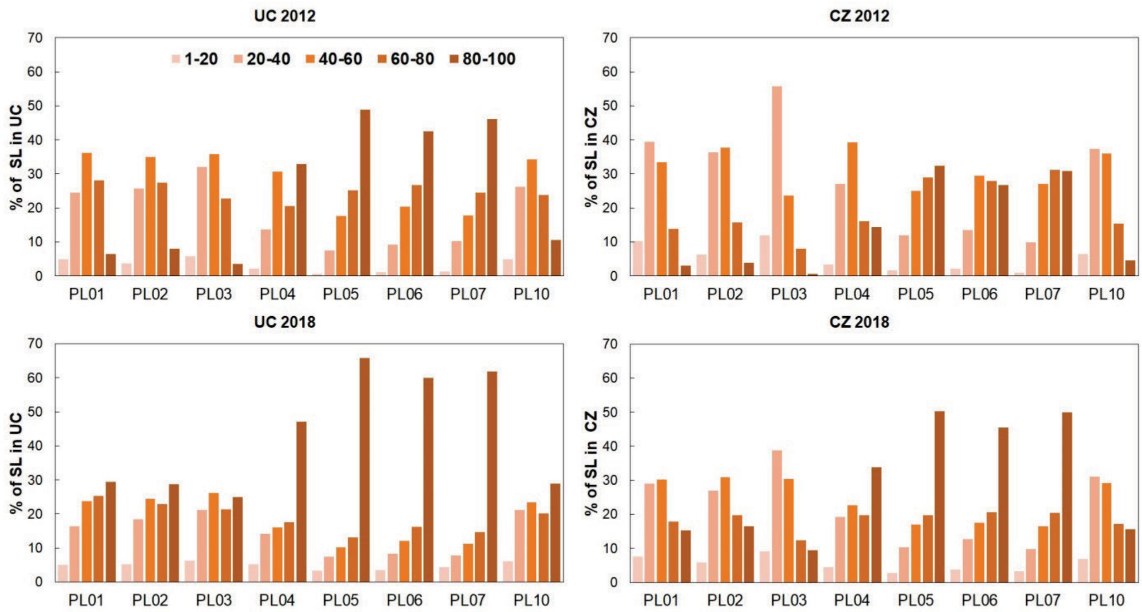

Fig. 2. The internal structure of totally sealed land (SL) in urban cores (UCs) and commuting zones (CZs) by the degree of sealing interval (1–20%, 20–40%, 40–60%, 60–80%, and 80–100%) according to the imperviousness density high resolution layer (HRL IMD) data in 2012 and 2018; PL01–PL10 as in Tab. 1; source: own study based on the EEA (2018) and EEA (2020a)

transformed space (Kudas and Wnęk, 2021). Stakeholders more and more often propose green belts be established around large metropolitan areas and towns to limit land take and soil sealing (EEA, 2012) and to offset intensive sealing near UCs.

ARTIFICIAL SURFACE MIX BASED ON UA AND BDOT10K DATA

The results from the UA data demonstrate a greater share of artificial surfaces in UCs and CZs than the results based on the BDOT10k data (Tab. 4). Taking into account the spatial resolutions of the databases, the results based on the BDOT10k database should be considered more realistic. They indicate the share of artificial surfaces in UCs of 23.28–45.89%. The results for 2012 and 2018 based on the UA data show that on average 1.3% of the UC area was converted into artificial surfaces, while in CZs, it was 0.7% of the area on average. According to the UA data, artificial surfaces grew on average by 0.78% of the area of the investigated FUA from 2012 to 2018. These results correspond to those by Wnęk, Kudas and Stych (2021), where the authors demonstrated an increase in artificial surfaces of 0.81% in 32 FUA in Poland from 2006 to 2012 with UA data.

According to the BDOT10k data, built-up areas (PTZB01–PTZB05) constitute from 7.3% for Wrocław to 13% for Katowice. Most FUA are dominated by single-family housing (PTZB02), taking up 6.3% of the FUA areas on average, followed by an average of 1% for multi-family housing (PTZB01), other buildings (PTZB05), and industrial and warehousing buildings (PTZB03). The share of built-up areas in UCs reaches from 16.4% (Szczecin)

Table 4. Percentage of artificial surfaces in individual functional urban areas (FUA) and their urban cores (UCs) and commuting zones (CZs) according to the Urban Atlas (UA) data for 2012 and 2018 and the National Database of Topographic Objects (BDOT10k)

Central city	FUA code	Share of artificial surfaces in zones (%)									Changes in the artificial surface share in the zones from 2012 to 2018 (%)		
		UA 2012			UA 2018			BDOT10k					
		FUA	UC	CZ	FUA	UC	CZ	FUA	UC	CZ	FUA	UC	CZ
Warsaw	PL01	15.21	62.00	12.22	15.68	63.29	12.64	11.94	45.89	9.77	0.48	1.29	0.43
Łódź	PL02	19.59	52.08	12.79	20.72	54.21	13.71	16.00	42.37	10.49	1.13	2.13	0.92
Kraków	PL03	17.64	51.75	14.39	18.39	53.17	15.08	12.56	37.33	10.20	0.75	1.42	0.69
Wrocław	PL04	13.88	50.39	9.34	14.64	51.35	10.08	9.64	31.19	6.96	0.76	0.95	0.73
Poznań	PL05	14.15	53.83	10.48	15.00	54.97	11.30	24.20	59.28	20.95	0.85	1.14	0.82
Gdańsk	PL06	15.61	43.81	12.50	16.63	45.93	13.39	11.53	30.03	9.49	1.01	2.12	0.89
Szczecin	PL07	14.66	34.57	7.44	15.22	35.24	7.95	10.37	23.28	5.68	0.55	0.67	0.51
Katowice	PL10	22.46	41.29	14.05	23.19	42.00	14.79	16.87	30.00	11.01	0.73	0.71	0.74
Mean		16.65	48.72	11.65	17.43	50.02	12.37	14.14	37.42	10.57	0.78	1.30	0.72

Source: own elaboration based on Urban Atlas data (EEA, 2016; EEA, 2020b) and BDOT10k data.

to 33.8% (Łódź) with a mean value of 25.4%. The dominant type of developments in UCs is single-family housing (10.5%) followed by multi-family housing (6.7%), other buildings (3.6%), industrial and warehousing buildings (3.3%), and commercial buildings (1.2%). Built-up areas constitute from 4.2% (Szczecin) to 9.1% (Kraków) of CZs. The mean share of individual types of developments is 5.6% for single-family housing, 0.7% for other buildings, 0.6% for industrial and warehousing buildings, 0.3% for multi-family housing, and 0.1% for commercial buildings. The building mix reflects CZ functions, especially through the substantial proportion of industrial and warehousing buildings and other buildings accompanied by a small share of multi-family housing. The least variable feature in both UCs and CZs is industrial and warehousing buildings with 19.4 and 20.4%, respectively, which reflects a supply and demand balance for such objects in both types of zones. It may also be because all the investigated cities except Warsaw are classified as tier II in the hierarchy of cities in Poland in terms of their services and functions. Some differences were found in the share of multi-family housing in CZs, which could reflect their varied development. The proportion of sealed surface classified as transport area (PTKM) in the investigated FUA ranges from 1% (Kraków) to 2.7% (Katowice). This type of infrastructure takes up from 3.7% (Szczecin) to 7.4% (Warsaw) of UCs and from 0.7% (Kraków) to 1.8% (Katowice) of CZs. On average, transport infrastructure takes up about 4.7% of UCs and 1.1% of CZs.

According to the 2012 UA data (EEA, 2016), road and rail network and associated land (122) constituted from 2.0% (Warsaw and Poznań) to 3.1% (Katowice) of the area of the FUA and from 4.6% (Szczecin) to 7.8% (Warsaw) of UCs area. In 2012, its share in CZs ranged from 1.5% (Szczecin and Poznań) to 2.1% (Katowice). The percentage of continuous urban fabric (111) was 20.9% for Warsaw and from 4.5% (Katowice, Szczecin) to 9.3% (Wrocław) for the remaining UCs in 2012. It was much smaller in CZs, where it varied from 0.6% (Łódź) to 2.6% (Warsaw). The mean proportion of continuous urban fabric was 8.5% in UCs and 1.2% in CZs. Additionally, the share of discontinuous urban fabric (112) in UCs was from 6.4% (Szczecin) to 17.2% (Łódź) and in CZs, it ranged from 2.5% (Szczecin) to 8.4% (Kraków). The mean share of these areas in UCs was 10.6% and in CZs, 4.9%. The UA data for 2018 (EEA, 2020b) show that the percentage of road and rail network and associated land in FUA increased to the range from 2.1% (Warsaw) to 3.2% (Katowice), which is from 4.7% (Szczecin) to 8.2% (Warszawa) for UCs and from 1.7% (Warsaw) to 2.1% (Katowice and Gdańsk) for CZs. In 2018, the mean share of road and rail network and associated land was 2.4% of the FUAs, 6.2% of UCs, and 1.8% of CZs. The mean share of continuous urban fabric in UCs was about 8.6% and in CZs, 1.2% in 2018. The increase was the greatest in the UCs of Wrocław (0.3%), Kraków (0.2%), and then Szczecin, Poznań, and Gdańsk (0.1%). Discontinuous urban fabric grew more because its mean proportion in UCs was about 11.4% and 5.3% in CZs. The largest increases in discontinuous urban fabric were found in the UCs of Gdańsk (1.3%), Łódź (1.1%), Warsaw (1.0%), and Kraków (0.8%). The other UCs had increases below 0.5%.

Typical urban developments are encroaching peri-urban areas, which may disturb the lives of people living there and necessitate infrastructure upgrades and expansions (Kudas and Wnęk, 2021). It is consistent with the greater increase in land under transport infrastructure in CZs than in UCs identified here in the UA data. As the UA data show (Tab. 4) the investigated FUA gained 196.5 km^2 of artificial surfaces in total from 2012 to 2018, including 42.1 km^2 in UCs, which is a 21% increase in artificial surfaces in the FUA. The largest growth in artificial surfaces is in CZs. Pearson correlation coefficients (r) confirm correlations between the share of land with 1–100% sealing (HRL IMD data) with the shares of artificial surfaces (BDOT10k and UA 2018 data) in UCs (r from 0.96 to 1.00) and to a lesser degree in CZs (r about 0.80). The results for the eight investigated FUA are consistent with data published in EEA Report (EEA, 2021). According to that, increase in land take in commuting areas of FUA in Poland in 2012–2018 is 6.27%, which place the country at the third position in EU-27 and the UK region, right after Romania and Lithuania.

RELATIONSHIP BETWEEN TOTALLY SEALED LAND AND ARTIFICIAL SURFACES

The ratio of sealed land to artificial surfaces computed based on the UA data show that SL constituted about 27.3% of artificial surfaces in the FUA in 2012, while in 2018, it grew to 31.6%. According to the BDOT10k data, SL occupies about 33.6% of artificial surfaces. Note that the SL percentage in artificial surfaces is nearly twice as large in UCs as in CZs. The mean increase in the SL share in artificial surfaces in the FUA from 2012 to 2018 is estimated at 4.3%. CZs exhibited a greater increase in the share of SL than UCs (Tab. 5). Soil sealing in artificial surfaces situated in CZs grew by about 6%, while in UCs, it was 2.2% over the study period. The high proportion of SL in artificial surfaces in UCs is very alarming. The shares of SL in artificial surfaces of UCs computed from the BDOT10k data and amounting to over 50% for Wrocław, Gdańsk, and Szczecin indicate that the percentage of vegetated areas in artificial surfaces is below 40% (Tab. 5). The UA data yielded lower shares of SL in artificial surfaces but they still reached nearly 50% in Poznań, Gdańsk, and Szczecin.

According to EEA Guidelines (EEA, 2012), cities should be expanded into poor-quality soils following local zoning plans, which should prevent building on high and very high-quality soils. Additional efforts should be made to preserve peri-urban agricultural zones by supporting internal urban growth with the intent to promote food security and sustainable agricultural land use. In Poland, a building permit for a structure or constructed feature requires the investor to file for approval of a plot plan or site development plan, where the share of developed and vegetated, green, areas is specified (Ustawa, 1994). The required share of vegetated areas is usually set to 25–75% depending on the zoning plan zone. In zones intended for multi-family buildings, health care buildings (except clinics) and education and upbringing buildings, at least 25% of the plot area should be designated as a biologically active area, unless a higher percentage results from the provisions of the local development plan (Obwieszczenie, 2022). For single-family development areas, local plans usually set the biologically active area at 60–75% of the plot area. Note, however, that the authorities do not strictly monitor conformity with zoning plan regulations because the owner is not obliged to report the as-is degree of soil sealing. In addition, not all FUA have 100% coverage of local zoning plans. For instance, Kraków is covered in 77.5% (Urząd Miasta Krakowa, 2023). Restrictions for new developments introduced with local zoning

Table 5. Percentage of totally sealed land (SL) in artificial surfaces (AS) in functional urban areas (FUA) and their urban cores (UCs) and commuting zones (CZs) according to the Urban Atlas data for 2012 (UA 2012) and 2018 (UA 2018) and the National Database of Topographic Objects (BDOT10k)

Central city	FUA code	Degree of soil sealing in artificial surfaces by zone (%)									Changes in the degree of soil sealing in artificial surfaces by zone from 2012 to 2018 (%)		
		UA 2012			UA 2018			BDOT10k					
		AS_{FUA}	AS_{UC}	AS_{CZ}	AS_{FUA}	AS_{UC}	AS_{CZ}	AS_{FUA}	AS_{UC}	AS_{CZ}	AS_{FUA}	AS_{UC}	AS_{CZ}
Warsaw	PL01	21.15	33.50	17.15	26.48	37.94	22.81	26.94	45.25	21.45	5.33	4.45	5.66
Łódź	PL02	21.00	29.12	14.08	24.08	31.10	18.27	25.71	35.79	17.18	3.08	1.98	4.18
Kraków	PL03	16.13	29.24	11.65	20.66	33.76	16.27	22.66	40.53	16.43	4.53	4.53	4.62
Wrocław	PL04	26.26	39.17	17.60	32.23	40.81	26.80	37.82	63.28	23.64	5.98	1.64	9.20
Poznań	PL05	35.85	48.81	29.69	41.09	49.16	37.46	20.96	44.33	14.84	5.24	0.35	7.77
Gdańsk	PL06	32.89	47.83	27.11	36.53	48.82	31.87	44.54	69.77	35.72	3.64	0.99	4.76
Szczecin	PL07	39.12	47.03	25.78	40.99	45.86	33.17	55.32	69.85	33.74	1.88	−1.17	7.39
Katowice	PL10	25.88	30.96	19.23	30.60	35.70	24.14	34.46	42.61	24.54	4.72	4.74	4.91
Mean		27.29	38.21	20.29	31.58	40.39	26.35	33.55	51.43	23.44	4.30	2.19	6.06

Source: own elaboration based on Urban Atlas data (EEA, 2016; 2020b) and BDOT10k data.

plans are a basic instrument for controlling flood impact (Szylar *et al.*, 2019). An increase in areas with soil sealed at 80–100%, which offer few vegetated areas will exacerbate repercussions for urban agglomerations. Lack of vegetated areas will contribute to urban temperature increase. Depriving the soil of its water-retaining potential through sealing will aggravate local inundations. It is alarming, that in the years 2012–2018, Poland experienced the second largest increase in artificial surfaces in EU-27 and UK region in protected areas within peri-urban areas, which is more than 1% (EEA, 2021). Therefore, it is important to restrict further transformations of urban green spaces to prevent soil sealing (Xiao, Tian and Xu, 2020) and to redevelop built-up land, including through brownfield revitalisation.

CONCLUSIONS

We confirmed that the period of 2012 to 2018 saw a trend towards soil sealing intensification in Poland because both supra-regional and capital cities went through an increase in areas sealed in 80–100% at the expanse of those with the degree of sealing ranging from 20 to 80%. Commuting zones of supra-regional cities went through a lesser intensification of sealing into 60–80% and 80–100% in place of areas sealed at 20–40%, 40–60% and 60–80%. We further demonstrated that despite the consistent positive trend in soil sealing, cities and peri-urban areas differ in terms of dynamics. Soil sealing in peri-urban zones grew by over 25% in six years. We also demonstrated that the area of artificial surfaces in the Polish functional urban areas (FUA) grew by 0.78% from 2006 to 2018, similar to 2006–2012. Moreover, it has been demonstrated that the profile of the artificial surface mix in the investigated supra-regional cities and their commuting zones varies, but developments encroach on peri-urban areas more boldly, leading to the sealing of vegetated areas.

The percentage of totally sealed surface in artificial surfaces varies, but in urban cores (UCs) it ranged from 35.79 to 69.85% according to the BDOT10k data and from 31.10 to 49.16% according to the Urban Atlas data in 2018. Note further that the share of totally sealed surface in artificial surfaces increased in every FUA from 2012 to 2018 on average by 4.3% of artificial surfaces. The increase in commuting zones (CZs) was greater (6.06% on average) than the increase in UCs, which was 2.19%. The results show that the high resolution layer imperviousness density (HRL IMD) data are recommended for determining the area of sealed soil in functional urban areas and commuting zones, while for urban cores, the equation of areas with sealed soil with artificial surfaces yields satisfactory results.

The present analysis quantifies the general degree of soil sealing in functional urban areas of supra-regional cities and provides insights for the formation of spatial policies in the key Polish urban agglomerations, especially concerning soil sealing prevention, including the implementation of the "Guidelines on best practice to limit, mitigate, or compensate soil sealing" and the "EU's soil strategy for 2030". Soil sealing and its negative impact on soil quality and functions can be limited in urban planning process mostly through the smart use of space and curbing of urban sprawl. Urban open spaces have to be protected, and cities with over 20% of sealed soil need to make an effort to restore vegetated areas by amending their planning documents. Stricter monitoring and record keeping of soil sealing in Poland is recommended both when approving building permit for a structure or constructed feature and after investments are completed.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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