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Carbon Footprint Assessment for Sustainable Spatial Management in Urban Settlements: Study of Polish Cities

Abstract: Urbanization significantly contributes to environmental changes, increasing carbon emissions, and resource consumption. This study quantifies the carbon footprints (CFs) and biocapacities (BCs) of urban settlements in Poland by focusing on household consumption levels in 18 regional cities.

The research assesses CF in categories like waste generation, energy use, mobility, and food consumption, converting it into global hectares [gha] in order to measure the environmental impact. BC is evaluated by land use types in order to understand urban sustainability.

The results showed considerable disparities, with Warsaw having the highest level CF and Zielona Góra the lowest. Mobility, electricity, and food contributed more than 80% of the total CF in our study. All of the cities exhibited ecological deficits, with CF levels exceeding those of BC; this indicated unsustainable resource use. Warsaw, for example, required more than 28 times its BC to support its consumption patterns.

The study emphasizes the need for targeted interventions in transportation, energy efficiency, and public awareness in order to reduce urban environmental impacts. Local governments must prioritize sustainability efforts – especially in high-impact sectors. The research highlights the importance of urban planning strategies that align with sustainability goals in order to achieve a long-term ecological balance and resilience against climate change, thus offering insights that could guide policy development beyond Poland.

Keywords: carbon footprint, spatial management, urban settlements, environmental impact, human impact, Earth overshoot, sustainable cities and communities

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1. Introduction

Urbanization is one of the most significant drivers of environmental changes in the 21st century. As cities grow and develop, they become hubs of economic activities, social transformations, and centers of intensified ecological pressure. The rapid expansion of urban areas often leads to increased carbon emissions due to higher energy consumption, transportation demands, and industrial activities [1, 2]. Recent studies have highlighted that urban centers account for more than 70% of global CO₂ emissions, which continue to rise with accelerating urbanization [3, 4]. Furthermore, urbanization accelerates the consumption of natural resources, thus contributing to deforestation, land degradation, and the over-exploitation of water and resources [5, 6]. This growth is often accompanied by ecological degradation, as the expansion of built environments interferes with natural habitats, thus reducing biodiversity and changing ecosystems [7, 8].

The concentration of populations and industries in urban areas results in the fact that cities are responsible for a disproportionate share of global greenhouse gas emissions [9], making them critical sites for addressing environmental sustainability. As the world continues to urbanize at an unprecedented rate [10], local governments are increasingly faced with the challenge of managing this growth in a way that balances development with ecological responsibility [11]. To achieve this, local authorities must prioritize high-emission areas such as industrial zones and transportation networks by implementing targeted interventions for reducing emissions and improving resource efficiency [12, 13]. These targeted interventions could be identified by carbon footprint quantification.

The carbon footprint (CF; full list of abbreviations available in Appendix A) concept is derived from the Ecological Footprint (EF) concept that was developed in the 1990s by W. Rees and M. Wackernagel [14]. EF was a theoretical framework for assessing the balance between human demand for natural resources and the planet's ability to regenerate them. It represents the amount of biologically productive land and water areas that are needed to supply the human population with natural resources [15]. The footprint is spatially and temporarily comparable with biocapacity [16, 17] – the actual potential of an area to provide resources. This is expressed in the same units; that is, global hectares [gha] [18–20]. The theory of the Ecological Footprint that was introduced by Rees and Wackernagel allowed for assessments of whether cities were living within the ecological limits of their environments or overshooting their biocapacities [21].

The concept of a carbon footprint can be interpreted in various ways, making it challenging to establish a consistent definition. Some approaches account for direct and indirect emissions or exclusively direct, calculating the emissions that are produced by a product or service over one or more stages of its life cycle [22]. The measurement can represent emissions per unit of production or consumption, product, service, process, or per capita depending on the requirements. The treatment of

individual greenhouse gases remains unresolved; some analyses consider only carbon dioxide emissions, while others account for gases such as methane and ozone (these are converted into carbon dioxide equivalents by using equivalence factors) [23, 24].

Reporting the carbon footprint is essential, as it constitutes more than 60% of the total global Ecological Footprint [19]; this represents 60% of the overall human impact on the environment [20]. Currently, the concept of the carbon footprint is gaining significance; this is partly due to the implementation of the Corporate Sustainability Reporting Directive (CSRD), which requires institutions to conduct non-financial reporting (particularly focusing on estimating the carbon dioxide equivalents of their annual activities) [25]. Moreover, the implementation of carbon taxes, emission-trading schemes, and mandatory reporting frameworks have intensified efforts to reduce carbon footprints across all industries [23]. International climate agreements such as the Paris Agreement have emphasized the necessity of reducing emissions to limit the rises in global temperatures, thus making carbon-footprint reduction a central focus for industries and governments [26].

Furthermore, the sustainable development goals (SDGs) have elevated the carbon footprint as a key metric in achieving sustainability targets – particularly, SDG 13 (on climate action) [27, 28]. The level of sustainability (Fig. 1) of a given area (city, region, country) could be verified by comparing footprint indicators (mainly, the Ecological Footprint) with the human development level that is expressed by the Human Development Index [29].



Fig. 1. Correlation of EF and HDI; green rectangle represents so-called global sustainable-development quadrant

Source: European Environment Agency, <https://www.eea.europa.eu/en/analysis/maps-and-charts/correlation-of-ecological-footprint-2008#references-and-footnotes>

A very high HDI (greater than or equal to 0.8) and an Ecological Footprint per capita that is smaller than the world biocapacity per capita are the minimum requirements for achieving sustainable development [30]; this represents the so-called global sustainable development quadrant.

Despite the growing body of research on urbanization's environmental impacts, there remains a critical gap in understanding how the carbon footprints of individual urban settlements compare to their biocapacities or the abilities of these regions to regenerate the resources that they consume [31–34]. Therefore, identifying targeted interventions is essential – not only for mitigating the immediate environmental impact of urbanization, but also for ensuring the long-term ecological balance that is required to sustain urban life [35, 36]. Urban areas have the potential to be drivers of environmental changes and pioneers of sustainable development and ecological stewardship [21].

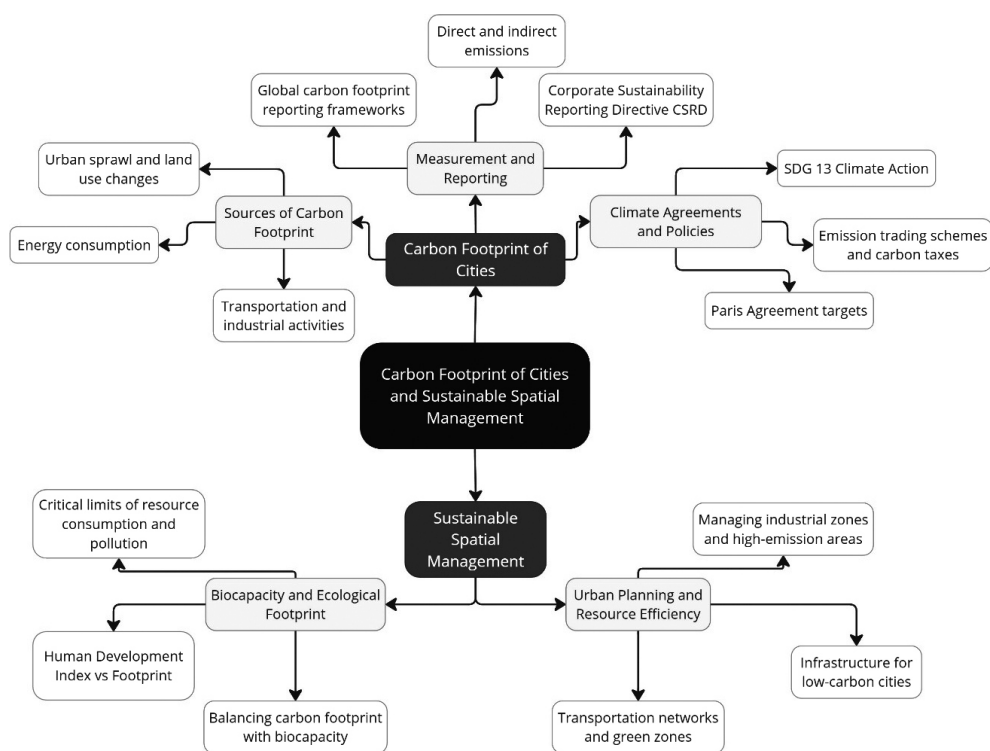


Fig. 2. Mind map based on literature review

Source: elaboration using AI (Diagrams & Data: Research, Analyze, Visualize) and Miro

Thus, the primary objective of the analysis in this research was to examine human impact on the environment through carbon footprint quantification. The study was conducted in all of Poland's regional cities, with a focus on household consumption. As a comparable indicator, biocapacity was used in assessing the human

impact. By using these two indicators, it was possible to determine the maximum capacity of the environment and the critical limits of anthropopression [37]. Maintaining a biocapacity that is higher than one's carbon footprint guarantees a state of equilibrium between man and nature [17]. The analysis will make it possible to determine the sources and limits of the pollution in cities and develop recommendations for more-sustainable urban development.

2. Materials and Methods

2.1. Study Area

The study area consisted of the main urban settlements – the capital cities of Poland's 16 regions (voivodeships). The analyses were contained to only within the administrative boundaries of these units and did not consider entire urban agglomerations or functional areas. The number of cities that were included in the analyses was 18 – Kuyavian-Pomeranian Voivodeship (where Bydgoszcz and Toruń are located) and Lubusz Voivodeship (where Gorzów Wielkopolski and Zielona Góra are located) each have two capitals. The population of Poland was set at 37,019,327 inhabitants in 2021 (GUS, 2022). In the same year, the collective population of the cities in the study area was 7,806,351 (Fig. 3).

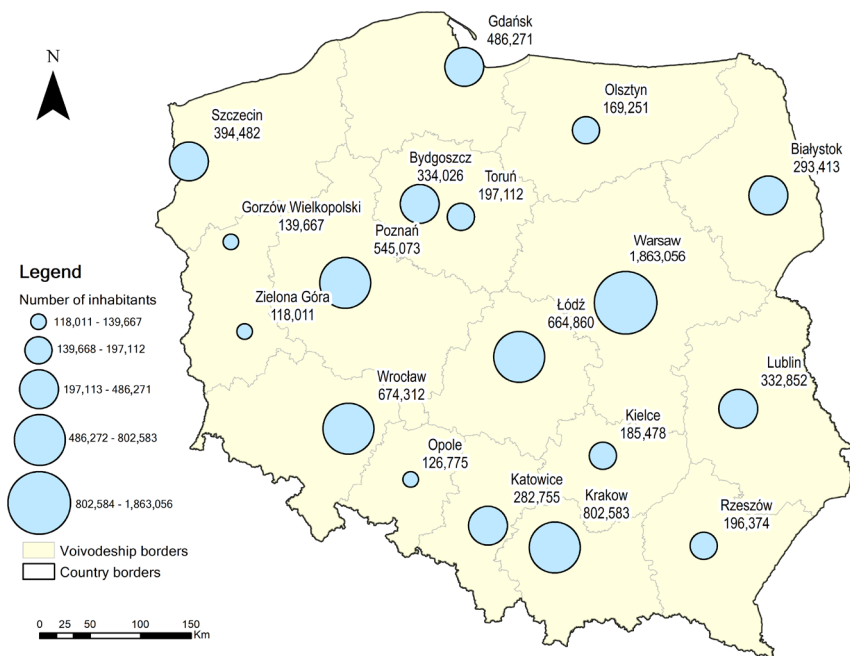


Fig. 3. Analyzed cities and their populations

Source: elaboration using QGIS

Therefore, the demographics of the analyzed units accounted for approximately 21.09% of the total population of the country. An analysis of the demographic changes over the past ten years (2012–2021) indicated that the population of the study area had been steadily declining. More than half of the cities (as many as 11) lost residents over the decade; only 7 cities recorded population growths over the decade (in descending order, these were Warsaw [with the greatest increase], followed by Krakow, Wrocław, Gdańsk, Gorzów Wielkopolski, Rzeszów, and Opole [with the smallest increase]).

Those cities with regularly declining populations accounted for the majority; among the factors that influenced the negative demographic trends of these urban units were:

- the losses of city-forming functions in favor of larger urban centers,
- suburbanization processes that led to the depopulations of urban centers,
- declining birth rates [38].

2.2. Data Acquisition and Preparation

For our analysis and calculations presented in this study, the following data from specific sources were used:

- population data for country, study area, and individual cities from National Population and Housing Census in 2021 (org. Narodowy Spis Ludności i Mieszkań; 2021; 2022);
- data on resource consumption (i.e., water, electricity, and gas); data on pollutant emissions (i.e., amounts of generated liquid and solid waste as well as number of passenger cars); data regarding consumption of selected foodstuffs per capita in households by class of locality for cities with populations of 100,000–499,000 and above 500,000 from Statistics Poland – Local Data Bank (org. Główny Urząd Statystyczny – Bank Danych Lokalnych; 2021);
- boundaries of study area from National Register of Boundaries (org. Państwowy Rejestr Granic);
- land-cover data for study area from Urban Atlas (2018) and from Copernicus Land Monitoring Service;
- data on yield factors (YF), equivalence factors (EQF), and global carbon sequestration rates from Global Footprint Network.

The data-preparation process for further analysis involved several steps: the non-spatial data was standardized into comparable units, thus allowing for easy comparisons and conversions (e.g., the monthly and annual food consumption data was aligned to a single time scale). Additionally, the spatial data was categorized by land use type according to Urban Atlas (UA) codes, which was required for the biocapacity assessment.

There were five land-use-type (LUT) categories [37] to which the following codes were assigned:

- 1) built-up land/infrastructure – 11100, 11210, 11220, 11230, 11240, 11300, 12100, 12210, 12220, 12230, 12300, 12400, 13100, 13300, and 13400;

2) grazing lands – 14100, 14200, 23000, 32000, and 33000;

3) croplands – 21000 and 22000;

4) forest lands – 31000;

5) inland and marine fishing grounds – 40000 and 50000
- (explanations of UA codes assigned to LUTs can be seen in Appendix B).

3. Methodology

Carbon Footprint Assessment

The carbon footprint assessment involved dividing the consumption patterns of the residents in the regional cities into seven categories: (1) liquid waste generation, (2) solid waste generation, (3) water, (4) electricity, (5) gas use, (6) pollution from personal transportation, and (7) food consumption [37]. These categories were chosen to reflect the growing daily consumption of natural resources that was required to meet residents’ basic needs as well as the associated pollution. This categorization formed the basis for evaluating the human environmental impact. Consequently, the resource use (Fig. 4; equation available in Appendix C) was quantified in terms of carbon dioxide equivalents and scaled globally using an equivalence factor and global sequestration rate (CO₂/ha). The resulting value represented the carbon footprint of each component [39].



Fig. 4. Scheme of carbon footprint assessment

Biocapacity Assessment

Assessing the biocapacity (BC) required the reclassification of land use data, where the 24 land use classes defined by the Urban Atlas were reorganized into five basic land use types (LUTs) as defined by the Global Footprint Network (Fig. 5); these were built-up land/infrastructure, grazing lands, croplands, forest lands, and inland and marine fishing grounds.

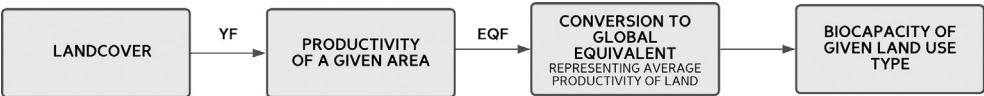


Fig. 5. Scheme of biocapacity assessment

Any newly designated LUT category had a yield factor that represented the annual productivity of the coverage class. Biocapacity was the result of the product of the area of a class, the yield factor, and the equivalence factor, which converted the national productivity yield into its global equivalent ([37]; equation available in Appendix C).

The land use structure played a key role in the final evaluation of the carbon footprint; it allowed for preliminary estimations of the biocapacities, which varied in each agglomeration. Those cities with the greatest shares of forest lands could have relatively higher ecological potentials (potentials to provide ecosystem services) due to the high yield factor for these cover categories. A large share of agricultural land and grazing lands would also translate positively into the final biocapacity scores, but not to such a high degree as those areas that were covered by forests due to the lower levels of YF. Built-up lands were assigned the same YF as croplands and were included in the total values of the biological potentials.

Defining State of Environment Using Footprint and Biocapacity

The difference between footprint (ecological or carbon) and biocapacity reflects the state of the environment – whether or not a population's consumption surpasses the available resources of a given area. A state where BC exceeds EF is referred to as an “ecological reserve,” while an EF that exceeds BC is known as an “ecological deficit.” When these two indicators are in relative equilibrium, the state is considered to be an “ecological balance” [37, 40]. The “ecological balance” state is possible when a minimum of 11% (the range is set at 11–75%) of land that provides environmental services is reserved for the restoration of environmental capacity [17]. Based on this environmental state, countries, regions, or cities can be classified as “ecological creditors” (those that consume fewer ecological resources than what is available within their borders, thereby generating ecological reserves) or “ecological debtors.”

4. Results

4.1. Overview of Carbon Footprint

Key Results

Representing the sum of all of the analyzed categories, the total carbon footprint serves as the final CF score for each city. Warsaw recorded the highest CF (3,163,637.285 gha), Krakow and Wrocław each exceeded 1 million gha, and Łódź and Poznań each totaled more than 900,000 gha. The coastal cities of Gdańsk and Szczecin also had significant carbon footprints – each surpassed 500,000 gha. Those cities with populations below 200,000 exhibited CFs that ranged from 178,000 to 287,000 gha. The gap between the highest and lowest CF scores was less than 3 million gha – equivalent to the difference between Warsaw and Zielona Góra. Warsaw alone accounted for 25% of the total carbon footprint in the study

area, with a CF score that was twice that of the combined total for Toruń, Zielona Góra, Gorzów Wielkopolski, Opole, Rzeszów, Kielce, and Olsztyn – 3.1 million gha vs. 1.6 million gha (Fig. 6).

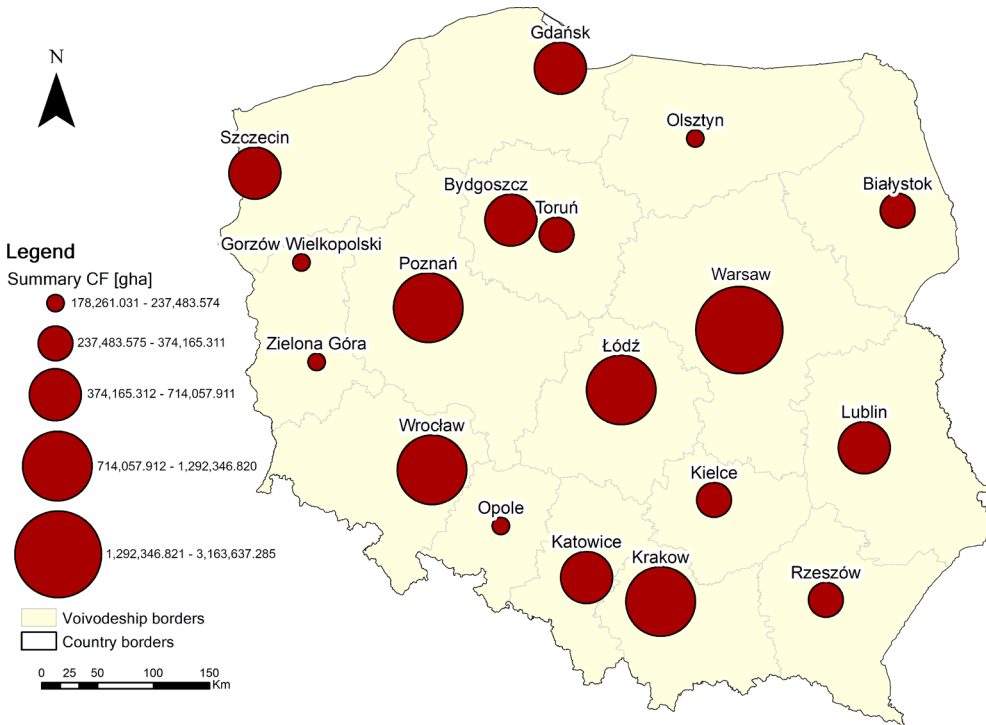


Fig. 6. Summary of carbon footprints of study area

Source: elaboration using QGIS

Category Breakdown

The areas of the urban lifestyle that had the greatest impact on the carbon footprints were mainly based on the use of energy resources such as electricity and gas and were connected with mobility as well as food (Table 1; more-detailed results for each CF component/category can be seen in Appendix D).

The category with the largest share of the total carbon footprint was mobility; it accounted for about 50.5% of the total carbon footprint, with a total of 6,218,290 gha. The next areas of similar high impact on the environment could be connected with electricity and food, which account for 17.3 and 16.7% of the total CF value, with a total of 2,127,535 gha and 2,055,921 gha, respectively. Gas consumption in the carbon footprint structure is 9.9% and accounts for 1,226,664 gha. The last and least important categories in the carbon footprint value are solid waste, water, and liquid waste, which represent about 4%, 0.5% and 0.01% of the total CF produced, given in total of 650,936 gha (Table 2).

Table 1. Total CF for each urban settlement

Urban settlements	CF of categories [gha]								Total CF	CF per capita
	Liquid waste	Solid waste	Water	Energy	Gas	Food	Mobility			
Wrocław	8610.82	62,200.13	5115.25	192,946.61	141,441.38	174,568.89	515,074.10	1,099,957.170	1.631	
Bydgoszcz	4253.59	17,748.68	2038.62	72,102.20	41,435.48	89,975.55	261,513.35	489,067.480	1.464	
Toruń	2140.37	13,135.50	1196.22	42,056.76	27,118.60	53,095.45	137,199.69	275,942.598	1.400	
Lublin	4054.83	20,246.15	1910.95	76,366.24	51,406.22	89,659.32	243,027.25	486,670.954	1.462	
Zielona Góra	2214.73	7987.82	677.52	27,416.69	12,216.40	31,894.53	95,853.35	178,261.031	1.511	
Gorzów Wielkopolski	1156.23	11,754.10	840.37	35,284.87	26,995.25	37,747.44	105,569.77	219,348.025	1.571	
Łódź	8602.08	44,701.49	4481.88	176,638.35	76,422.05	172,121.91	499,793.26	982,761.020	1.478	
Krakow	10,359.80	53,035.79	6143.65	249,441.41	139,099.12	207,776.25	626,490.79	1,292,346.820	1.610	
Warsaw	25,342.74	108,202.26	13,908.09	599,590.23	292,572.70	482,316.22	1,641,705.05	3,163,637.285	1.698	
Opole	1613.24	6971.58	920.17	34,588.03	19,096.89	34,263.15	115,909.92	213,362.988	1.683	
Rzeszów	2376.90	8256.66	1333.93	42,669.71	36,740.71	53,073.49	142,593.72	287,045.128	1.462	
Białystok	3079.89	18,572.87	1760.40	59,232.48	37,767.30	79,035.76	174,716.61	374,165.311	1.275	
Gdańsk	4747.43	25,995.47	3361.84	120,054.87	58,248.31	130,985.32	370,664.67	714,057.911	1.468	
Katowice	3532.83	18,052.23	1881.70	80,150.71	47,407.27	76,164.84	261,634.26	488,823.849	1.729	
Kielce	2865.31	12,653.24	1148.00	40,962.37	28,520.69	50,128.66	135,881.42	272,159.684	1.467	
Olsztyn	1838.45	9657.79	1027.14	36,080.93	24,018.69	45,743.03	119,117.55	237,483.574	1.403	
Poznań	7019.86	36,544.17	3758.97	146,425.28	100,160.42	141,110.92	489,520.43	924,540.045	1.696	
Szczecin	4747.91	22,649.08	2509.62	95,527.69	65,996.67	106,260.40	282,024.45	579,715.813	1.470	

Highest values highlighted in gray

Source: own compilation based on GUS 2021 data

Table 2. Total CF – component share

Category	CF of categories [gha]						
	Liquid waste	Solid waste	Water	Energy	Gas	Food	Mobility
Mean	5475.39	27,686.95	3000.80	118,196.41	68,148.01	114,217.84	345,460.54
Sum	98,557.01	498,365.02	54,014.32	2,127,535.42	1,226,664.14	2,055,921.13	6,218,289.64
Share [%]	0.01	4.06	0.44	17.33	9.99	16.74	50.64

Highest values highlighted in gray

Source: own compilation based on GUS 2021 data

The urban settlements with the highest total per capita carbon footprints (Table 1) were Katowice (1.729 gha), Warsaw (1.698 gha), Poznań (1.696 gha), Opole (1.683 gha), and Wrocław (1.610 gha); Poznań, Warsaw, and Wrocław were in the group of cities with more than 500,000 residents, and Opole, and Katowice were classified in the group of cities with 100,000–499,000 residents. On the other hand, the lowest CF per capita results were achieved by cities such as Białystok (1.275 gha), Toruń (1.400 gha), and Olsztyn (1.403 gha); all of these were cities in the group of 100,000–499,000 residents. The average per capita score for all of the analyzed cities was 1.527 gha.

4.2. Biocapacity Analysis

The land use structure of the study area was created based on the 24 land-cover classes that were defined by Urban Atlas (such as discontinuous urban fabric, port areas, construction sites, and wetlands). The classification was reduced to five LUTs: built-up lands/infrastructures, grazing lands, croplands, forest lands, and inland and marine fishing grounds.

The settlement units were covered to the greatest extent by built-up lands – 151,561.50 ha; this accounted for an approximately 39.90% coverage of the entire study area. The second-most-extensive category was grazing lands – 85,393.19 ha; its percentage result in the LUT structure was 22.48%.

A slightly smaller area of urban land was covered by forest lands – 79,651.47 ha (which accounted for 20.96%). Due to the urban nature of the settlement units, a relatively small percentage of the area was covered by croplands – occupying 46,840.85 ha (12.30%). The last category of land cover (covering only 16,464.01 ha) was inland and marine fishing grounds, which accounted for 4.33% of the LUT structure of the study area (Table 3).

Zielona Góra stood out among the cities; despite being the smallest urban settlement in our study, it had the second-highest biocapacity score (69,295.329 gha). Warsaw (the capital city of Poland) recorded the highest biocapacity, with a score of 114,429.845 gha. Other cities with notable biocapacity scores included Łódź and Krakow (both exceeding 60,000 gha). In contrast, cities with lower biological potentials included Gorzów Wielkopolski, Olsztyn, Kielce, Rzeszów, Toruń, and Białystok; these biocapacities ranged from 16,000 to 30,000 gha (Table 4, Fig. 7).

Table 3. Land use structure of study area by urban settlements

Urban settlements	LUT									
	Forest lands		Inland and marine fishing grounds		Croplands		Built-up lands		Grazing lands	
	ha	%	ha	%	ha	%	ha	%	ha	%
Zielona Góra	16,355.87	58.80	43.82	0.16	2611.47	9.39	4192.55	15.07	4613.00	16.58
Opole	1762.81	11.84	447.62	3.01	6355.25	42.70	4319.15	29.02	1999.41	13.43
Gorzów Wlkp.	665.87	7.77	136.54	1.59	1884.36	21.98	2945.04	34.35	2942.48	34.32
Olsztyn	2589.64	29.35	779.58	8.84	463.44	5.25	3061.75	34.71	1927.70	21.85
Kielce	2590.29	23.65	51.67	0.47	467.63	4.27	4490.10	40.99	3353.23	30.61
Rzeszów	757.87	5.88	137.30	1.06	3050.80	23.65	5630.68	43.66	3320.42	25.75
Toruń	3375.58	29.21	682.86	5.91	990.61	8.57	4522.22	39.13	1985.02	17.18
Katowice	7655.77	46.54	198.37	1.21	462.00	2.81	6103.82	37.10	2030.27	12.34
Białystok	1945.43	19.04	67.63	0.66	461.81	4.52	5377.50	52.63	2365.40	23.15
Lublin	1797.32	12.19	335.30	2.27	2701.89	18.32	6687.19	45.34	3226.30	21.88
Bydgoszcz	5903.43	33.59	670.62	3.82	2554.73	14.54	6470.32	36.82	1973.45	11.23
Szczecin	6575.91	21.87	8052.47	26.78	846.45	2.81	7955.35	26.45	6642.07	22.09
Gdańsk	5231.77	19.87	1386.04	5.27	3785.62	14.38	10,029.18	38.10	5892.77	22.38
Poznań	4297.85	16.42	754.36	2.88	3457.72	13.21	11,787.49	45.05	5869.94	22.43
Łódź	3955.82	13.51	67.10	0.23	5075.27	17.33	13,653.21	46.62	6533.17	22.31
Wrocław	2760.22	9.44	730.55	2.50	4919.04	16.81	11,706.89	40.02	9137.30	31.23
Kraków	2114.73	6.48	710.75	2.18	3780.63	11.58	14,926.50	45.73	11,110.29	34.04
Warsaw	9315.29	18.03	1211.43	2.34	2972.14	5.75	27,702.61	53.61	10,470.97	20.26
Study area	79,651.47	20.96	16,464.01	4.33	46,840.85	12.30	151,561.50	39.93	85,393.19	22.48

Highest share of given land use type for each city highlighted in gray [%]

Source: own compilation based on Urban Atlas 2018 data

Table 4. Total BC according to LUTs

Urban settlements	BC – LUTs [gha]						Total BC	Total BC per capita
	Forest lands	Inland and marine fishing grounds	Croplands	Built-up lands/ infrastructures	Grazing lands			
Zielona Góra	47,820.273	16.187	6522.113	10,470.831	4465.925		69,295.329	0.587
Opole	5153.983	165.343	15872.138	10,787.021	1935.664		33,914.150	0.268
Gorzów Wielkopolski	1946.829	50.436	4706.153	7355.195	2848.664		16,907.276	0.121
Olsztyn	7571.433	287.965	1157.423	7646.686	1866.243		18,529.751	0.109
Kielce	7573.322	19.086	1167.910	11,213.954	3246.315		23,220.586	0.125
Rzeszów	2215.824	50.717	7619.334	14,062.558	3214.557		27,162.991	0.138
Toruń	9869.323	252.238	2474.041	11,294.189	1921.728		25,811.520	0.131
Katowice	22,383.466	73.275	1153.850	15,244.204	1965.536		40,820.332	0.144
Białystok	5687.918	24.980	1153.365	13,430.224	2289.988		22,586.475	0.077
Lublin	5254.902	123.854	6747.934	16,701.155	3123.435		31,951.280	0.096
Bydgoszcz	17,260.092	247.716	6380.396	16,159.547	1910.532		41,958.283	0.126
Szczecin	19,226.249	2974.469	2114.002	19,868.383	6430.303		50,613.405	0.128
Gdańsk	15,296.333	511.985	9454.534	25,047.735	5704.893		56,015.480	0.115
Poznań	12,565.804	278.650	8635.610	29,439.089	5682.792		56,601.946	0.104
Łódź	11,565.772	24.787	12,675.408	34,098.709	6324.879		64,689.554	0.097
Wrocław	8070.176	269.855	12,285.237	29,237.798	8845.978		58,709.043	0.087
Kraków	6182.913	262.542	9442.066	37,278.724	10,756.059		63,922.304	0.080
Warsaw	27,235.458	447.484	7422.885	69,186.893	10,137.125		114,429.845	0.061

Highest values highlighted in gray

Source: own compilation based on Urban Atlas 2018

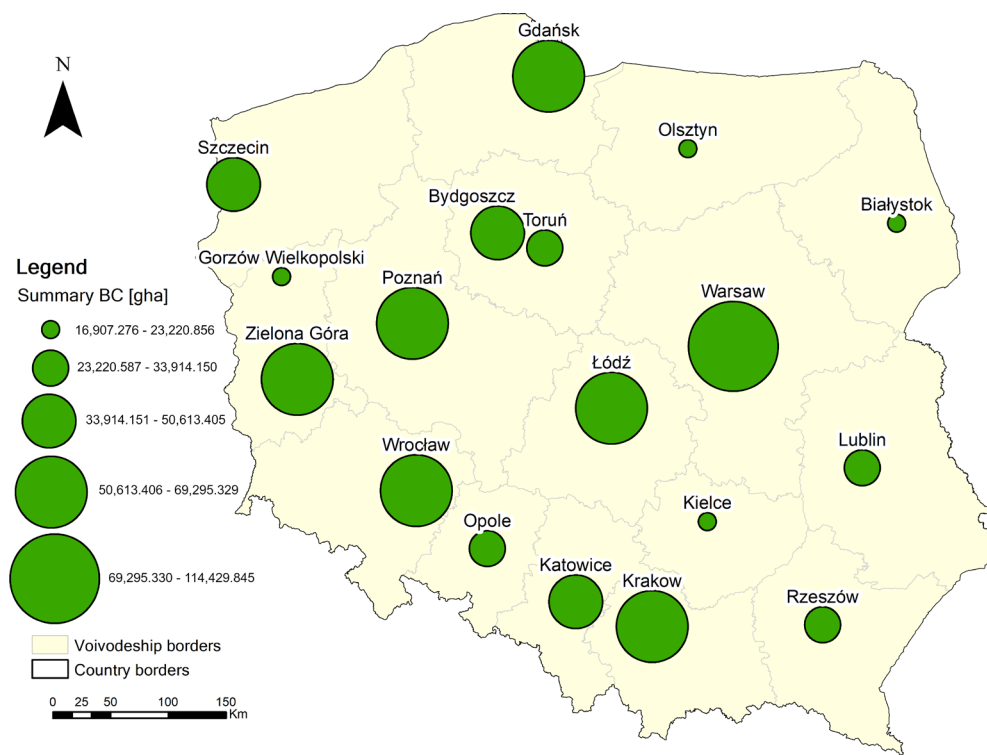


Fig. 7. Total biocapacity of study area

Source: elaboration using QGIS

The average value of the total biocapacity per capita for the study area was 0.144 gha; none of the cities exceeded 1 gha per capita. Zielona Góra had the highest value (0.587 gha), while Warsaw had the lowest (0.061 gha).

4.3. Environmental State Assessment

Comparison of CFs and BCs across Cities

A comparison of the total results of the carbon footprints and biocapacities that were available within the urban settlements showed a large disparity between these two indicators within the administrative boundaries of the cities. The total carbon footprint was 12,279,346.69 gha, while the biocapacity was 817,139.55 gha. On average, the urban units of the study area showed 15-times-smaller values of the sums of the biocapacities relative to the carbon footprints that they generated (Table 5). The state of the environment, which indicates the difference between the carbon footprint and the biocapacity with an environmental reserve of 11% to ensure the maintenance of biodiversity, did not indicate a state of ecological reserve in any of the surveyed cities.

Table 5. Environmental state – CF vs. BC

Urban settlements	Total CF	Total BC	Difference (CF-BC)	Difference decreased by 11% of BC (CF – BC')	Environmental state
Zielona Góra	178,261.031	69,295.329	-108,965.702	-116,588.188	ecological deficit
Opole	213,362.988	33,914.150	-179,448.838	-183,179.395	ecological deficit
Gorzów Wielkopolski	219,348.025	16,907.276	-202,440.749	-204,300.549	ecological deficit
Olsztyn	237,483.574	18,529.751	-218,953.823	-220,992.096	ecological deficit
Kielce	272,159.684	23,220.586	-248,939.098	-251,493.362	ecological deficit
Rzeszów	287,045.128	27,162.991	-259,882.137	-262,870.066	ecological deficit
Toruń	275,942.598	25,811.520	-250,131.078	-252,970.346	ecological deficit
Katowice	488,823.849	40,820.332	-448,003.517	-452,493.754	ecological deficit
Białystok	374,165.311	22,586.475	-351,578.836	-354,063.348	ecological deficit
Lublin	486,670.954	31,951.280	-454,719.674	-458,234.315	ecological deficit
Bydgoszcz	489,067.480	41,958.283	-447,109.197	-451,724.608	ecological deficit
Szczecin	579,715.813	50,613.405	-529,102.408	-534,669.882	ecological deficit
Gdańsk	714,057.911	56,015.480	-658,042.432	-664,204.135	ecological deficit
Poznań	924,540.045	56,601.946	-867,938.100	-874,164.314	ecological deficit
Łódź	982,761.020	64,689.554	-918,071.466	-925,187.317	ecological deficit
Wrocław	1,099,957.170	58,709.043	-1,041,248.127	-1,047,706.122	ecological deficit
Kraków	1,292,346.820	63,922.304	-1,228,424.516	-1,235,455.969	ecological deficit
Warsaw	3,163,637.285	114,429.845	-3,049,207.440	-3,061,794.723	ecological deficit
Study area	12,279,346.686	817,139.549	-11,462,207.137	-11,552,092.487	ecological deficit

Source: own compilation based on Urban Atlas 2018 and GUS 2021 data

All of the units were characterized by so-called ecological deficits at high levels. There was a noticeable trend in the comparison that indicated that the ecological deficit increased as the population of an agglomeration increased.

Global Comparisons

The quotient of the carbon footprint and biocapacity (Table 6) determined the state of the environment through the number of Earth-sized planets that would be required to meet the needs of a particular city (or the entire study area). The results of the carbon footprint of the study area could be compared to global and/or national biocapacity; this was intended to represent whether the amount of available BC on Earth or in a country would be sufficient in a situation where all of the inhabitants of the globe or country would live in the same manner as the inhabitants of the individual cities of our study area.

Table 6. Comparison of CF results of study area with BCs of study area, Poland, and world

CF and BC at different levels [gha per capita]						Comparison of study area's CF vs. BC at different levels [no. of Earth-sized planets]		
Study area's CF per capita (2021)	Poland's CF per capita (2021)	World's CF per capita (2021)	Study area's BC per capita (2018)	Poland's BC per capita (2021)	World's BC per capita (2021)	CF vs. study area's BC	CF vs. Poland's BC	CF vs. world's BC
1.527	2.76	1.56	0.144	2.1	1.52	10.604	0.727	1.004

Source: own compilation based on Urban Atlas 2018, GUS 2021, and Global Footprint Network

The average per capita carbon footprint of the study area was 1.527 gha; at the same time, the average biological potential per capita was 0.144 gha. The quotient of the carbon footprint and biological potential (1.527/0.144) meant how many Earth-sized planets would be needed to meet the needs of the inhabitants of the study area (Table 6); in this case, **10.604** Earth-sized planets would be necessary in order to meet the needs of all of the inhabitants of the provincial cities.

The results were different when compared to the national and global potentials; if all of the residents of the country presented CFs at the level of the study area (1.527 gha) with a national BC of 2.1 gha, the number of Earth-sized planets would amount to **0.727**. If the CFs of the provincial cities were juxtaposed with the global BC (1.52 gha), **1.004** Earth-sized planets would be required (Table 6).

The amount of resources that were required to meet the needs of the residents in this study varied significantly among the urban units (Table 7); e.g., Warsaw would require **28.33** planets, while Zielona Góra would require **2.56**. Warsaw and Zielona Góra are examples of how large differences can occur between a city with a low urbanization coefficient and a high degree of forest cover and a city with an almost completely urbanized area; Warsaw's score exceeded that of Zielona Góra 11-fold.

Table 7. Environmental state – comparison of CF vs. BC individual city results

Urban settlement	City's CF per capita 2021	City's BC per capita 2018	City's CF vs. study area's BC	City's CF vs. Poland's BC	City's CF vs. world's
Zielona Góra	1.51	0.59	2.57	0.72	0.99
Opole	1.68	0.27	6.29	0.80	1.11
Gorzów Wielkopolski	1.57	0.12	12.97	0.75	1.03
Olsztyn	1.40	0.11	12.82	0.67	0.92
Kielce	1.47	0.13	11.72	0.70	0.97
Rzeszów	1.46	0.14	10.57	0.70	0.96
Toruń	1.40	0.13	10.69	0.67	0.92
Katowice	1.73	0.14	11.98	0.82	1.14
Białystok	1.28	0.08	16.57	0.61	0.84
Lublin	1.46	0.10	15.23	0.70	0.96
Bydgoszcz	1.46	0.13	11.66	0.70	0.96
Szczecin	1.47	0.13	11.45	0.70	0.97
Gdańsk	1.47	0.12	12.75	0.70	0.97
Poznań	1.70	0.10	16.33	0.81	1.12
Łódź	1.48	0.10	15.19	0.70	0.97
Wrocław	1.63	0.09	18.74	0.78	1.07
Kraków	1.61	0.08	20.22	0.77	1.06
Warsaw	1.70	0.06	27.65	0.81	1.12

Highlighted cells reflect state of environment: red – ecological deficit; green – ecological reserve

Source: own compilation based on Urban Atlas 2018, GUS 2021, and Global Footprint Network

All of the voivodeship capitals were characterized by ecological deficits, thus indicating the shortages of raw materials and natural components within their borders. Most of the agglomerations were characterized by scores that exceeded ten planets; only two units (i.e., Zielona Góra and Opole, which were also the smallest voivodeship cities) scored below this ten-planet threshold (2.57 and 6.29 planets, respectively).

A comparison of the carbon footprint per capita of the urban settlements and the biocapacity per capita of the entire country showed positive relationships in all of the city units – states of ecological reserve in all cases. When comparing the carbon footprint per capita of the analyzed cities to the global biocapacity per capita, seven cities exceeded the requirements of one Earth-sized planet: Katowice, Poznań, Warsaw, Opole, Wrocław, Krakow, and Gorzów Wielkopolski. The remaining urban units had scores that were below the one-planet threshold, but they were very close to it.

The greatest amount of environmental resources would be required if all of the inhabitants lived in the same way that the inhabitants of Katowice did (1.14 planets), while the lowest amount would be necessary if all of the inhabitants lived in the same manner as the inhabitants of Białystok did (0.84 planets) (Table 7).

5. Discussion

In recent years, there has been increasing awareness of the need to reduce our vulnerability and enhance our resilience in response to social and environmental challenges as well as the impact of human activities on both the people and the environment [41–43]. A key response to these challenges was the Corporate Sustainability Reporting Directive (CSRD), which was introduced on January 5, 2023, in an effort to modernize and strengthen the regulations that govern the social and environmental information that companies are required to report [25]. These efforts were part of a broader movement toward more-sustainable spatial management, including initiatives by local authorities to implement knowledge-based green-action plans [44, 45]. Such plans have been developed based on analyses of human environmental impacts by using metrics like the ecological or carbon footprints [31]. Carbon footprint assessments can particularly serve as valuable decision-making tools for highly urbanized areas [46–48], including the main urban centers that were evaluated in this study.

The total carbon footprints that were generated by the voivodeship cities were closely correlated with their population sizes. In every consumption category that was analyzed, the aggregate scores followed an upward trend: the larger the city, the higher its overall carbon footprint. However, a few cities deviated from this pattern due to their unique characteristics; e.g., Katowice, where the per capita carbon footprint was notably high (likely a result of its industrial and mining activities). By

comparing the results and assessing the consumption patterns of the residents in these cities, it is possible to calculate the per capita carbon footprint of each city; this perspective revealed insights into the lifestyles of the inhabitants. A low total carbon footprint did not always translate to a low per capita footprint (as could be seen in cities like Zielona Góra, Gorzów Wielkopolski, and Opole, where the respective per capita values exceeded the study area's average). Conversely, some cities with high total carbon footprints (such as Łódź) showed lower per capita values as compared to the study area's average.

The aggregated biocapacity for the regional cities was characterized by greater irregularity due to the greater number of factors that shaped the final results; these included the land use structure, the values for the yield and equivalence factors, or the area of the city in question, for example.

The average carbon footprint per capita for the voivodeship capitals was quantified at 1.527 gha; the maximum was 1.73 gha (Katowice), and the minimum – 1.4 gha (Olsztyn and Toruń). Thus, the average for the Polish cities was close to the average per capita carbon footprint value for the world (1.56 gha). On the other hand, the average values of the biocapacity per capita for the voivodeship centers was 0.144 gha, with a maximum value of 0.59 gha (Zielona Góra) and a minimum of 0.06 gha (Warsaw). These values were significantly lower than the national value (2.1 gha for Poland) and world value (1.52 gha). Especially in terms of biocapacity, these differences indicated how much of a negative impact that urbanized areas had on the environment [48] – primarily the largest urban settlements.

The study indicated that the manufacturing and mining city of Katowice had the highest impact, with an environmental impact of 1.729 gha per capita. In second place was the city of Warsaw, with a value of 1.698 gha per capita; this may seem surprising given that the city of Warsaw could be characterized by a higher level of public awareness than smaller cities like Opole (which ranked fourth in the carbon footprint ranking). Lower impacts would also be expected from cities such as Poznań (1.696 gha per capita – the third-highest emissions), Wrocław (1.631 gha – fifth position), and Krakow (1.610 gha – sixth position), as these are all academic cities. Thus, one would expect higher public awareness given that these are among the largest cities in Poland on the one hand and academic communities that are increasingly aware and actively participate in events for a better future on the other.

The presentation of the carbon footprint and biocapacity results showed the general ecological deficit of the study area, which occurred separately in each studied voivodeship capital. The resultant differences that indicated the state of the environment within the boundaries of the studied urban units were so great that it was impossible to reduce them to the levels of ecological reserves. Each major city was, therefore, an ecological debtor that required the import of raw materials from outside its borders in order to maintain further growth. This is a worldwide trend, which indicates that cities are the largest environmental debtors [46, 49]; their

impacts may increase in the future due to the urban population growth that has been projected by 2050 [50]. The proportion of the population in urbanized areas could reach 68%, thus, the environmental impact could intensify without changing any current living habits or lifestyles [51].

Fossil-fuel-based consumption categories accounted for approximately 80% of the total carbon footprint, with mobility contributing 50.6%, electricity consumption 17.3%, and gas consumption 9.9%. These high percentages highlight the sectors where changes and regulations are most needed to optimize the use of resources. Other studies have also confirmed that the most carbon-intensive activities are related to electricity consumption [52], transportation, and food consumption [53, 54].

The carbon footprint studies have highlighted the significant environmental impact of the average household in Poland; each of the included cities in the analysis exceeded its biocapacity, thus indicating a state of ecological deficit. Poland's major urban centers are ecological debtors to varying degrees, thus also placing substantial pressure on their surrounding areas; i.e., their urban-rural fringes. The recommended actions should be implemented not only in those cities that are experiencing ecological deficits but also across all urban and suburban areas. Particularly, suburban residents can significantly influence the environmental and functional impacts of cities – especially those who commute to larger urban centers using individual transportation. As was indicated, an average of 13% of the population in Poland commutes daily from suburban areas to their jobs in larger cities; for instance, this accounted for an additional 25% of Bielsko-Biała's population (64,500 commuters versus 256,000 residents), 20% of Rzeszów's (84,600 vs. 432,000), and 19% of Poznań's (201,400 vs. 1,042,000) in 2006 [55]. Consequently, it is not only the congestion that is caused by the daily commuting from suburban areas to city centers that is a major problem [56, 57]; the associated GHG pollution that is introduced into the environment from road vehicles is also an issue [58].

Efforts to reduce the carbon footprints and improve the environmental sustainabilities of cities should focus on multiple fronts. Reducing individual transportation by expanding public transit options is essential, as is increasing the numbers of intercity connections – especially since 14 million Poles currently lack access to public transportation [59]. The popularization of Park-and-Ride systems can further aid this effort, along with initiatives to curb local migration and encourage the reurbanization of depopulating cities through resident incentives [60]. Enhancing the efficiency of urban district-heating networks by connecting more residential buildings, supporting passive construction for greater household energy efficiency, and replacing outdated heating units in city centers with more-efficient models are also crucial steps [61]. Raising public awareness about energy and environmental issues through campaigns that address appliance efficiency, water consumption, and food consumption can foster more-sustainable practices [62]. Additionally, improving local government oversight regarding waste segregation and disposal alongside

programs that promote waste segregation culture is necessary [63, 64]. Revitalizing degraded brownfield sites and converting them into urban green spaces [65] can improve urban ecosystems, as can expanding blue-green infrastructures for rainwater retention [66]. Preserving nature by protecting existing forest complexes, maintaining ecological and ventilation corridors, and restoring biodiversity are also vital steps [67]. Finally, increasing the coherence of planning documents will ensure that these efforts are consistently supported [39].

6. Conclusion

In the face of rising environmental issues and a fast-growing global population, it is crucial to limit the unsustainable exploitation of our world's natural resources. A society must be directed toward protecting the planet's biodiversity and reducing the impacts of climate change. Given that the environment is integral to human well-being, our actions must prioritize efficiency, sustainability, and (most importantly) awareness. Central to this shift is the role of education, which should emphasize the principles of sustainable development and foster knowledge-based decision-making.

Carbon footprint assessment has emerged as a critical tool in guiding sustainable development practices. However, its ultimate usefulness is dependent on the accuracy of the measurements and the consistency of the calculation methods. While there are certain limitations to this tool, its integration has significantly contributed toward fostering more-responsible and ecologically mindful consumption and production patterns.

The findings of this study have underscored that transportation, energy consumption, and food systems are the predominant contributors to the carbon footprints of urban settlements. This highlights the urgent need for targeted interventions in these sectors in order to reduce emissions. Local governments therefore play important roles in prioritizing and implementing emission-reduction initiatives. In particular, improved urban-planning strategies are essential for mitigating the environmental impacts of urbanization.

These insights have broader implications beyond the immediate context, offering valuable lessons for cities across Europe and around the globe. As urban centers continue to expand, the adoption of more-sustainable practices and policies will be key for reducing their overall carbon footprints and fostering long-term environmental resilience.

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CRediT Author Contribution

M. M.: conceptualization, methodology, software, resources, data curation, formal analysis, investigation, software, visualization, writing – original draft preparation, writing – review and editing.

M. Ś.: conceptualization, methodology, software, resources, supervision, validation, visualization, writing – original draft preparation, writing – review and editing, funding acquisition.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work that is reported in this paper.

Data Availability

The data that supports the findings of this study was derived from the following resources which are available in the public domain:

- National Population and Housing Census (org. Narodowy Spis Ludności i Mieszkań; 2021): https://spis.gov.pl/aktualnosci/wyniki_03_01/;
- Statistics Poland – Local Data Bank (org. Główny Urząd Statystyczny – Bank Danych Lokalnych; 2021): <https://stat.gov.pl/en/>;
- Statistics Poland (org. Główny Urząd Statystyczny; 2022): <https://stat.gov.pl/obszary-tematyczne/ludnosc/ludnosc/ludnosc-rezydujaca-dane-nsp-2021,44,1.html>;
- National Register of Boundaries (org. Państwowy Rejestr Granic): <https://www.geoportal.gov.pl/en/data/national-register-of-boundaries/>;
- Urban Atlas (2018): <https://land.copernicus.eu/en/products/urban-atlas/urban-atlas-2018>;
- Global Footprint Network: <https://www.footprintnetwork.org/licenses/>.

Moreover, the authors confirm that some of the data that supports the findings of this study is available within the article and/or its supplementary materials.

Use of Generative AI and AI-Assisted Technologies

The research used AI technologies – for the English revision, Chat GPT 4.O was used, and for generating the mind map (Fig. 2), a tool called “Diagrams & Data: Research, Analyze, Visualize” was used, which was available on Chat GPT 4.O. Then, the figure was updated using Miro.

References

- [1] Seto K.C., Churkina G., Hsu A., Keller M., Newman P.W.G., Qin B., Ramaswami A.: *From low- to net-zero carbon cities: The next global agenda*. Annual Review of Environment and Resources, vol. 46, 2021, pp. 377–415. <https://doi.org/10.1146/annurev-environ-050120-113117>.

-
- [2] United Nations Department of Economic and Social Affairs, Population Division: *World Urbanization Prospects*. New York 2019.
- [3] Sovacool B.K., Brown M.A.: *Twelve metropolitan carbon footprints: A preliminary comparative global assessment*. *Energy Policy*, vol. 38(9), 2010, pp. 4856–4869. <https://doi.org/10.1016/J.ENPOL.2009.10.001>.
- [4] Luqman M., Rayner P.J., Gurney K.R.: *On the impact of urbanisation on CO₂ emissions*. *npj Urban Sustainability*, vol. 3, 2023, 6. <https://doi.org/10.1038/s42949-023-00084-2>.
- [5] Ekka P., Patra S., Upreti M., Kumar G., Kumar A., Saikia P.: *Land degradation and its impacts on biodiversity and ecosystem services*, [in:] Raj A., Jhariya M.K., Banerjee A., Nema S., Bargali K. (eds.), *Land and Environmental Management through Forestry*, Wiley, Hoboken 2023, pp. 77–101. <https://doi.org/10.1002/9781119910527.ch4>.
- [6] Seto K.C., Güneralp B., Hutyrá L.R.: *Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools*. *Proceedings of the National Academy of Sciences*, vol. 109(40), 2012, pp. 16083–16088. <https://doi.org/10.1073/pnas.1211658109>.
- [7] Sylla M., Lasota T., Szezwrański S.: *Valuing environmental amenities in peri-urban areas: Evidence from Poland*. *Sustainability*, vol. 11(3), 2019, 570. <https://doi.org/10.3390/su11030570>.
- [8] Grimm N.B., Faeth S.H., Golubiewski N.E., Redman C.L., Wu J., Bai X., Briggs J.M.: *Global change and the ecology of cities*. *Science*, vol. 319(5864), 2008, pp. 756–760. <https://doi.org/10.1126/science.1150195>.
- [9] IPCC: *Summary for Policymakers*, [in:] Edenhofer O., Pichs-Madruga R., Sokona Y., Farahani E., Kadner S., Seyboth K., Adler A., Baum I., Brunner S., Eickemeier P., Kriemann B., Savolainen J., Schlömer S., von Stechow C., Zwickel T., Minx J.C. (eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom, New York, NY, USA 2014, pp. 1–32.
- [10] Angel S., Parent J., Civco D.L., Blei A., Potere D.: *The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050*. *Progress in Planning*, vol. 75(2), 2011, pp. 53–107. <https://doi.org/10.1016/J.PROGRESS.2011.04.001>.
- [11] Creutzig F., Roy J., Lamb W.F., Azevedo I.M.L., de Bruin W.B., Dalkmann H., Edelenbosch O.Y., Geels F.W., Grübler A., Hepburn C., Hertwich G.E., Khosla R., Mattauch L., Minx J.C., Ramakrishnan A., Rao N.D., Steinberger J.K., Tavoni M., Ürge-Vorsatz D., Weber E.U.: *Towards demand-side solutions for mitigating climate change*. *Nature Climate Change*, vol. 8(4), 2018, pp. 268–271. <https://doi.org/10.1038/s41558-018-0121-1>.

- [12] Ma W., de Jong M., de Bruijne M., Mu R.: *Mix and match: Configuring different types of policy instruments to develop successful low carbon cities in China*. Journal of Cleaner Production, vol. 282, 2021, 125399. <https://doi.org/10.1016/J.JCLEPRO.2020.125399>.
- [13] Liu W., Qin B.: *Low-carbon city initiatives in China: A review from the policy paradigm perspective*. Cities, vol. 51, 2016, pp. 131–138. <https://doi.org/10.1016/J.CITIES.2015.11.010>.
- [14] Collins A., Flynn A.: *The ecological footprint : New developments in policy and practice*. Edward Elgar Publishing, Cheltenham, Northampton 2015.
- [15] Gao T., Liu Q., Wang J.: *A comparative study of carbon footprint and assessment standards*. International Journal of Low-Carbon Technology, vol. 9(3), 2014, pp. 237–243. <https://doi.org/10.1093/ijlct/ctt041>.
- [16] Mancini M.S., Galli A., Niccolucci V., Lin D., Bastianoni S., Wackernagel M., Marchettini N.: *Ecological footprint: Refining the carbon footprint calculation*. Ecological Indicators, vol. 61(2), 2016, pp. 390–403. <https://doi.org/10.1016/J.ECOLIND.2015.09.040>.
- [17] Świąder M., Szewrański S., Kazak J., van Hoof J., Lin D., Wackernagel M., Alves A.: *Application of ecological footprint accounting as a part of an integrated assessment of environmental carrying capacity: A case study of the footprint of food of a large city*. Resources vol. 7(3), 2018, 52. <https://doi.org/10.3390/resources7030052>.
- [18] Wackernagel M., Lin D., Evans M., Hanscom L., Raven P.: *Defying the footprint oracle: Implications of country resource trends*. Sustainability, vol. 11(7), 2019, 2164. <https://doi.org/10.3390/su11072164>.
- [19] Solarin S.A., Gil-Alana L.A., Lafuente C.: *Persistence in carbon footprint emissions: An overview of 92 countries*. Carbon Management, vol. 10(4), 2019, pp. 405–415. <https://doi.org/10.1080/17583004.2019.1620038>.
- [20] Dembińska I., Kauf S., Tłuczak A., Szopik-Decpzyńska K., Marzantowicz Ł., Ioppolo G.: *The impact of space development structure on the level of ecological footprint – shift share analysis for European Union countries*. Science of the Total Environment, vol. 851(2), 2022. <https://doi.org/10.1016/j.scitotenv.2022.157936>.
- [21] Rees W., Wackernagel M.: *Urban ecological footprints: Why cities cannot be sustainable – And why they are a key to sustainability*. Environmental Impact Assessment Review, vol. 16(4–6), 1996, pp. 223–248. [https://doi.org/10.1016/S0195-9255\(96\)00022-4](https://doi.org/10.1016/S0195-9255(96)00022-4).
- [22] Høgevoid N.M.: *A corporate effort towards a sustainable business model: A case study from the Norwegian furniture industry*. European Business Review, vol. 23(4), 2011, pp. 392–400. <https://doi.org/10.1108/09555341111145771>.
- [23] Ertung E.A., Hoekstra A.Y.: *Carbon and Water Footprints: Concepts, Methodologies and Policy Responses*. UNESCO World Water Assessment Programme, Paris 2012.

-
- [24] Frączek K., Śleszyński J.: *Carbon footprint indicator and the quality of energetic life*. Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu, nr 435, 2016, pp. 136–151. <https://doi.org/10.15611/pn.2016.435.09>.
- [25] *Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting*. OJ L 322, 16.12.2022. <http://data.europa.eu/eli/dir/2022/2464/oj>.
- [26] Matemilola S., Fadeyi O., Sijuade T.: *Paris Agreement*, [in:] Idowu S.O., Capaldi N., Zu L., Del Baldo M., Abreu R (eds.), *Encyclopedia of Sustainable Management*, Springer, Cham 2020, pp. 1–6. https://doi.org/10.1007/978-3-030-02006-4_516-1.
- [27] *Transforming Our World: The 2030 Agenda for Sustainable Development*. United Nations, 2015.
- [28] Wiedmann T., Allen C.: *City footprints and SDGs provide untapped potential for assessing city sustainability*. Nature Communications, vol. 12(1), 2021, 3758. <https://doi.org/10.1038/s41467-021-23968-2>.
- [29] *Correlation of Ecological Footprint (2008) and the Human Development Index (2012)*. European Environment Agency. 11.09.2024. <https://www.eea.europa.eu/en/analysis/maps-and-charts/correlation-of-ecological-footprint-2008> [access: 14.01.2025].
- [30] Moran D.D., Wackernagel M., Kitzes J.A., Goldfinger S.H., Boutaud A.: *Measuring sustainable development – nation by nation*. Ecological Economics, vol. 64(3), 2008, pp. 470–474. <https://doi.org/10.1016/j.ecolecon.2007.08.017>.
- [31] Moore J., Kissinger M., Rees W.E.: *An urban metabolism and ecological footprint assessment of Metro Vancouver*. Journal of Environmental Management, vol. 124, 2013, pp. 51–61. <https://doi.org/10.1016/j.jenvman.2013.03.009>.
- [32] Hammond G.P., Iddenden T., Wildblood J.: *Environmental and resource burdens associated with an urban community and its surrounding bioregion*. Energy Procedia, vol. 143, 2017, pp. 481–486. <https://doi.org/10.1016/j.egypro.2017.12.714>.
- [33] Kovács Z., Farkas J.Z., Szigeti C., Harangozó G.: *Assessing the sustainability of urbanization at the sub-national level: The ecological footprint and biocapacity accounts of the Budapest Metropolitan Region, Hungary*. Sustainable Cities and Society, vol. 84, 2022, 104022. <https://doi.org/10.1016/j.scs.2022.104022>.
- [34] Vigier M., Ouellet-Plamondon C.M., Spiliotopoulou M., Moore J., Rees W.E.: *To what extent is sustainability addressed at urban scale and how aligned is it with Earth's productive capacity?* Sustainable Cities and Society, vol. 96, 2023, 104655. <https://doi.org/10.1016/j.scs.2023.104655>.
- [35] Wiedmann T., Barrett J.: *A review of the ecological footprint indicator-perceptions and methods*. Sustainability, vol. 6(2), 2010 pp. 1645–1693. <https://doi.org/10.3390/su2061645>.

- [36] Kennedy C., Pincetl S., Bunje P.: *The study of urban metabolism and its applications to urban planning and design*. Environmental Pollution, vol. 159(8–9), 2011, pp. 1965–1973. <https://doi.org/10.1016/j.envpol.2010.10.022>.
- [37] Świąder M., Lin D., Szewrański S., Kazak J.K., Iha K., van Hoof J., Belčáková I., Altioek S.: *The application of ecological footprint and biocapacity for environmental carrying capacity assessment: A new approach for European cities*. Environmental Science & Policy, vol. 105, 2020, pp. 56–74. <https://doi.org/10.1016/j.envsci.2019.12.010>.
- [38] Zborowski A., Raźniak P.: *Suburbanizacja rezydencjonalna w Polsce – ocena procesu* [Residential suburbanization in Poland – estimate of proces]. Studia Miejskie, t. 9, 2013, pp. 37–50.
- [39] Świąder M., Szewrański S., Kazak J.K.: *Environmental carrying capacity assessment – the policy instrument and tool for sustainable spatial management*. Frontiers in Environmental Science, vol. 8, 2020, 579838. <https://doi.org/10.3389/fenvs.2020.579838>.
- [40] Pourebrahim S., Hadipour M., Emlaei Z., Heidari H., Goh C.T., Lee K.E.: *Analysis of environmental carrying capacity based on the ecological footprint for the sustainable development of Alborz, Iran*. Sustainability, vol. 15(10), 2023, 7935. <https://doi.org/10.3390/su15107935>.
- [41] Szewrański S., Świąder M., Kazak J.K., Tokarczyk-Dorociak K., van Hoof J.: *Socio-environmental vulnerability mapping for environmental and flood resilience assessment: The case of ageing and poverty in the city of Wrocław, Poland*. Integrated Environmental Assessment and Management, vol. 14(5), 2018, pp. 592–597. <https://doi.org/10.1002/ieam.4077>.
- [42] Carmen E., Fazey I., Ross H., Bedinger M., Smith F.M., Prager K., McClymont K., Morrison D.: *Building community resilience in a context of climate change: The role of social capital*. AMBIO: A Journal of the Human Environment, vol. 51, 2022, pp. 1371–1387. <https://doi.org/10.1007/s13280-021-01678-9>.
- [43] Sharifi A., Allam Z., Bibri S.E., Khavarian-Garmsir A.R.: *Smart cities and Sustainable Development Goals (SDGs): A systematic literature review of co-benefits and trade-offs*. Cities, vol. 146(3), 2024, 104659. <https://doi.org/10.1016/j.cities.2023.104659>.
- [44] Arciniegas G., Wascher D., Eyre P., Sylla M., Vicente-Vicente J.L., Świąder M., Unger T., Prag A.A., Lysák M., Schafer L.J., Welker E., Sanz E.S., Henriksen C.B.: *A participatory tool for assessing land footprint in city-region food systems – a case study from metropolitan Copenhagen*. Frontiers in Sustainable Food Systems, vol. 6, 2022, 846869. <https://doi.org/10.3389/fsufs.2022.846869>.
- [45] Kazak J.K., Świąder M., Arciniegas G., Aslanoğlu R., Wascher D., Chrobak G.: *The application of geoplanner in the management of local development*. Acta Scientiarum Polonorum Administratio Locorum, vol. 22(4), 2023, pp. 525–535. <https://doi.org/10.31648/aspal.9012>.

-
- [46] Galli A., Iha K., Moreno Pires S., Mancini M.S., Alves A., Zokai G., Lin D., Murthy A., Wackernagel M.: *Assessing the ecological footprint and biocapacity of Portuguese cities: Critical results for environmental awareness and local management*. Cities, vol. 96, 2020, 102442. <https://doi.org/10.1016/j.cities.2019.102442>.
- [47] Buzási A., Pálvölgyi T., Csete M.S.: *Assessment of climate change performance of urban development projects – case of Budapest, Hungary*. Cities, vol. 114, 2021, 103215. <https://doi.org/10.1016/j.cities.2021.103215>.
- [48] Shtjefni D., Ulpiani G., Vetter N., Koukoulakis G., Bertoldi P.: *Governing climate neutrality transitions at the urban level: A European perspective*. Cities, vol. 148, 2024, 104883. <https://doi.org/10.1016/j.cities.2024.104883>.
- [49] Vigier M., Ouellet-Plamondon C.M., Spiliotopoulou M., Moore J., Rees W.E.: *To what extent is sustainability addressed at urban scale and how aligned is it with Earth's productive capacity?* Sustainable Cities and Society, vol. 96, 2023, 104655. <https://doi.org/10.1016/j.scs.2023.104655>.
- [50] Solecka I., Sylla M., Świąder M.: *Urban sprawl impact on farmland conversion in suburban area of Wrocław, Poland*. IOP Conference Series: Materials Science and Engineering, vol. 245(7), 2017, 072002. <https://doi.org/10.1088/1757-899X/245/7/072002>.
- [51] Bhojar S.P., Dusad S., Shrivastava R., Mishra S., Gupta N., Rao A.B.: *Understanding the impact of lifestyle on individual carbon-footprint*. Procedia – Social and Behavioral Sciences, vol. 133, 2023, pp. 47–60. <https://doi.org/10.1016/J.SBSPRO.2014.04.168>.
- [52] Moore J.: *Ecological footprints and lifestyle archetypes: Exploring dimensions of consumption and the transformation needed to achieve urban sustainability*. Sustainability, vol. 7(4), 2015, pp. 4747–4763. <https://doi.org/10.3390/su7044747>.
- [53] Baabou W., Grunewald N., Ouellet-Plamondon C., Gressot M., Galli A.: *The ecological footprint of Mediterranean cities: Awareness creation and policy implications*. Environmental Science & Policy, vol. 69, 2017, pp. 94–104. <https://doi.org/10.1016/j.envsci.2016.12.013>.
- [54] Genta C., Sanyé-Mengual E., Sala S., Lombardi P.: *The consumption footprint as possible indicator for environmental impact evaluation at city level. The case study of Turin (Italy)*. Sustainable Cities and Society, vol. 79, 2022, 103679. <https://doi.org/10.1016/j.scs.2022.103679>.
- [55] Śleszyński P.: *Delimitation and typology of functional urban regions in Poland based on commuting*, 2006. Geographia Polonica, vol. 87, 2014, pp. 317–320. <https://doi.org/10.7163/GPol.2014.20>.
- [56] Marcińczak S., Bartosiewicz B.: *Commuting patterns and urban form: Evidence from Poland*. Journal of Transport Geography, vol. 70, 2018, pp. 31–39. <https://doi.org/10.1016/j.jtrangeo.2018.05.019>.
- [57] Wolny A.: *Are suburban commuters confined to private transport? A case study of a medium-sized functional urban area (FUA) in Poland*. Cities, vol. 92, 2019, pp. 82–96. <https://doi.org/10.1016/j.cities.2019.03.013>.

- [58] Szagała P., Brzeziński A., Dybicz T., Olszewski P., Osińska B.: *Problems with implementation of sustainable urban mobility in selected Polish cities*. Sustainability, vol. 16(24), 2014, 11003. <https://doi.org/10.3390/su162411003>.
- [59] Fedoruk A.: *14 milionów Polaków nie ma na co dzień dostępu do transportu publicznego*. Forbes, 8.10.2018. <https://www.forbes.pl/gospodarka/14-milionow-polakow-nie-ma-na-co-dzien-dostepu-do-transportu-publicznego/6r7jjxw> [access: 15.01.2025].
- [60] Ercan T., Onat N.C., Tatari O.: *Investigating carbon footprint reduction potential of public transportation in United States: A system dynamics approach*. Journal of Cleaner Production, vol. 133, 2016, pp. 1260–1276. <https://doi.org/10.1016/j.jclepro.2016.06.051>.
- [61] Dang L.M., Nguyen L.Q., Nam J., Nguyen T.N., Lee S., Song H.K., Moon H.: *Fifth generation district heating and cooling: A comprehensive survey*. Energy Reports, vol. 11, 2024, pp. 1723–1741. <https://doi.org/10.1016/j.egyr.2024.01.037>.
- [62] Pan A., Xu S., Zaidi S.A.H.: *Environmental impact of energy imports: natural resources income and natural gas production profitability in the Asia-Pacific economic cooperation countries*. Geoscience Frontiers, vol. 15(2), 2024, 101756. <https://doi.org/10.1016/j.gsf.2023.101756>.
- [63] Anuardo R.G., Espuny M., Costa A.C.F., Oliveira O.J.: *Toward a cleaner and more sustainable world: A framework to develop and improve waste management through organizations, governments and academia*. Heliyon, vol. 8(4), 2022, e09225. <https://doi.org/10.1016/j.heliyon.2022.e09225>.
- [64] Xiao L., Fu B., Lin T., Meng L., Zhang O., Gao L.: *Promoting and maintaining public participation in waste separation policies – a comparative study in Shanghai, China*. Resources, Environment and Sustainability, vol. 12, 2023, 100112. <https://doi.org/10.1016/j.resenv.2023.100112>.
- [65] Chowdhury S., Kain J.H., Adelfio M., Volchko Y., Norrman J.: *Greening the browns: A bio-based land use framework for analysing the potential of urban brownfields in an urban circular economy*. Sustainability, vol. 12(15), 2020, 6278. <https://doi.org/10.3390/SU12156278>.
- [66] Belčáková I., Świąder M., Bartyna-Zielińska M.: *The green infrastructure in cities as a tool for climate change adaptation and mitigation: Slovakian and Polish experiences*. Atmosphere (Basel), vol. 10(9), 2019, 552. <https://doi.org/10.3390/atmos10090552>.
- [67] Di Sacco A., Hardwick K.A., Blakesley D., Brancalion P.H.S., Breman E., Cecilio Rebola L., Chomba S., Dixon K., Elliott S., Ruyonga G., Shaw K., Smith P., Smith R.J., Antonelli A.: *Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits*. Global Change Biology, vol. 27(7), 2021, pp. 1328–1348. <https://doi.org/10.1111/gcb.15498>.

Appendix A:

List of Abbreviations

BC	– Biocapacity
CF	– Carbon footprint
CSRD	– Corporate Sustainability Reporting Directive
EF	– Ecological footprint
EQF	– Equivalence factor
gha	– Global hectares
GUS	– Główny Urząd Statystyczny (Eng. – Statistics Poland)
HDI	– Human Development Index
LUT	– Land use type
SDG	– Sustainable Development Goal
UA	– Urban Atlas
YF	– Yield factor

Appendix B:

Numerical Codes of Land Cover according to Urban Atlas (UA) Assigned to Given Land Use Type (LUT)

B.1. LUT: Built-up Land/Infrastructure – Assigned UA Codes

11100	– Continuous urban fabric (S.L. >80%)
11210	– Discontinuous dense urban fabric (S.L. 50–80%)
11220	– Discontinuous medium-density urban fabric (S.L. 30–50%)
11230	– Discontinuous low-density urban fabric (S.L. 10–30%)
11240	– Discontinuous very-low-density urban fabric (S.L. <10%)
11300	– Isolated structures
12100	– Industrial, commercial, public, military, and private units
12210	– Fast transit roads and associated lands
12220	– Other roads and associated lands
12230	– Railways and associated lands
12300	– Port areas
12400	– Airports
13100	– Mineral-extraction and dump sites
13300	– Construction sites
13400	– Lands without current use

B.2. LUT: Grazing Lands – Assigned UA Codes

14100 – Green urban areas

14200 – Sports and leisure facilities

23000 – Pastures

32000 – Herbaceous vegetation associations (natural grassland and moors)

33000 – Open spaces with little or no vegetation (beaches, dunes, bare rocks, and glaciers)

B.3. LUT: Croplands – Assigned UA Codes

21000 – Arable land (annual crops)

22000 – Permanent crops (vineyards, fruit trees, and olive groves)

B.4. LUT: Forest Lands – Assigned UA Codes

31000 – Forests

B.5. LUT: Inland and Marine Fishing Grounds – Assigned UA Codes

40000 – Wetlands

50000 – Water bodies

Appendix C:

Equations for Calculating Carbon Footprints of Individual Components and Biocapacities

To calculate the carbon footprint of liquid waste, the necessary information was the amount of total waste discharged; this was converted as follows:

$$CF_S = I_N \cdot A_S \cdot A_{SEL} \cdot I_{ELCO2eq} \cdot 10^{-3} \cdot EQF \cdot Is_{CO_2} \quad (C.1)$$

where:

CF_S – carbon footprint of sewage generation [gha],

I_N – number of inhabitants in given municipality [–],

A_S – average annual amount of sewage generated by inhabitants in given municipality [dam³],

A_{SEL} – coefficient of energy required to collect and treat 1 m³ of liquid waste [kWh/m³],

$I_{ELCO2eq}$ – total emissions of CO₂ in tons generated per 1 GWh [tCO₂/GWh],

EQF – equivalence factor for forest land use type [–],

Is_{CO_2} – global carbon dioxide sequestration rate [gha/tCO₂].

Solid waste was divided into categories of mixed waste and that which was sorted and collected separately; namely, paper/cardboard, glass, plastics, metals, and textiles.

$$CF_{Gb} = \Sigma \left(A_{Gbm} \cdot I_{Gbm_{CO_2eq}} \cdot EQF \cdot Is_{CO_2} \right) \quad (C.2)$$

where:

- CF_{Gb} – carbon footprint of garbage generation [gha],
- A_{Gbm} – annual amount of given garbage fraction generated from households in given municipality [t],
- $I_{Gbm_{CO_2eq}}$ – total emission of CO_2 in tons generated per 1 t of given garbage fraction [tCO_2/t],
- EQF – equivalence factor for forest land use type [–],
- Is_{CO_2} – global carbon dioxide sequestration rate [gha/ tCO_2].

The carbon footprint of water consumption was calculated based on consumption per household inhabitant in cubic meters:

$$CF_W = I_N \cdot A_W \cdot A_{WEL} \cdot I_{EL_{CO_2eq}} \cdot 10^{-6} \cdot EQF \cdot Is_{CO_2} \quad (C.3)$$

where:

- CF_W – carbon footprint of water use [gha],
- I_N – number of inhabitants in given municipality [–],
- A_W – average annual amount of water used by inhabitants in given municipality [m^3],
- A_{WEL} – coefficient of energy required to deliver 1 m^3 of water [kWh/m^3],
- $I_{EL_{CO_2eq}}$ – total emissions of CO_2 in tons generated per 1 GWh [tCO_2/GWh],
- EQF – equivalence factor for forest land use type [–],
- Is_{CO_2} – global carbon dioxide sequestration rate [gha/ tCO_2].

The carbon footprint of electricity consumption was calculated based on consumption in household per capita in kilowatt-hours [kWh]:

$$CF_{EL} = I_N \cdot A_{EL} \cdot I_{EL_{CO_2eq}} \cdot 10^{-6} \cdot EQF \cdot Is_{CO_2} \quad (C.4)$$

where:

- CF_{EL} – carbon footprint of electricity use [gha],
- I_N – number of inhabitants in given municipality [–],
- A_{EL} – average annual amount of electricity used by inhabitants in given municipality [kWh],
- $I_{EL_{CO_2eq}}$ – total emissions of CO_2 in tonnes generated per 1 GWh [tCO_2/GWh],
- EQF – equivalence factor for forest land use type [–],
- Is_{CO_2} – global carbon dioxide sequestration rate [gha/ tCO_2].

The carbon footprint of gas consumption was calculated based on per capita household consumption in kilowatt-hours [kWh]:

$$CF_G = I_N \cdot A_{GkWh} \cdot I_{GkWh} \cdot I_{G_{CO_2eq}} \cdot 10^{-3} \cdot EQF \cdot Is_{CO_2} \quad (C.5)$$

where:

- CF_G – carbon footprint of gas supply [gha],
- I_N – number of inhabitants in given municipality [–],
- A_{GkWh} – average annual amount of gas used by inhabitants in given municipality [kWh],
- I_{GkWh} – conversion factor kilowatt-hours to gigajoules (1 kWh = 0.0036 GJ),
- $I_{G_{CO_2eq}}$ – total emissions of CO₂ in kilograms generated per 1 GJ of gas [kgCO₂/GJ],
- EQF – equivalence factor for forest land use type [–],
- Is_{CO_2} – global carbon dioxide sequestration rate [gha/tCO₂].

The category of individual transportation was divided into the number of registered cars according to the type of propulsion that was used in each (diesel, gasoline, or propane):

$$CF_{CU} = \Sigma \left(C_N \cdot A_F \cdot F_F \cdot 10^{-6} \cdot I_{K_{CO_2eq}} \cdot EQF \cdot Is_{CO_2} \right) \quad (C.6)$$

where:

- CF_{CU} – carbon footprint of car use [gha],
- C_N – number of registered cars according to given fuel type in given municipality [–],
- A_F – average annual fuel consumption for car with 1.4–2.0 liter engine [L]:
 - gasoline: 1200,
 - diesel: 1050,
 - propane: 1800,
- F_F – conversion factor from liter of fuel to megajoule [MJ/L]:
 - gasoline: 32.2,
 - diesel: 35.9,
 - propane: 23.3,
- $I_{K_{CO_2eq}}$ – average CO₂ emissions generated per driven kilometer [tCO₂/TJ]:
 - gasoline: 73.1,
 - diesel: 74.0,
 - propane: 65.5,
- $EQF = 1.2793$ [–],
- $Is_{CO_2} = 0.334$ [gha/tCO₂].

As it was the most extensive consumption category, food was classified according to the consumption of the most common food commodities: beef, pork, poultry, milk, cheese, vegetable fats, sugar, bread, potatoes, citrus fruits/bananas, apples, coffee, and beer obtained from malt:

$$CF_{FC} = \Sigma \left(I_N \cdot A_F \cdot I_{CO_2} \cdot 10^{-3} \cdot EQF \cdot Is_{CO_2} \right) \quad (C.7)$$

where:

- CF_{FC} – carbon footprint of food consumption [gha],
- I_N – total number of inhabitants [–],
- A_F – annual weighted average amount of given consumed food in kilograms or liters per inhabitant [kg(L)],
- I_{CO_2} – equivalent of CO_2 (CO_2eq) in kilograms generated per kilogram or liter of given food at all levels of production and consumption [kg CO_2 /kg(L)],
- EQF – equivalence factor for forest land use type [–],
- Is_{CO_2} – global carbon dioxide sequestration rate [gha/t CO_2].

The following formula is needed to calculate the biocapacity:

$$BC = \Sigma \left(A_{LU} \cdot YF_{LU} \cdot EQF_{LU} \right) \quad (C.8)$$

where:

- BC – biocapacity [gha],
- A_{LU} – area of given land use type [ha],
- YF_{LU} – yield factor for given land use type,
- EQF_{LU} – equivalence factor for given land use type.

Appendix D: Detailed Results for Each Component/Category

D.1. CF of Liquid Waste

The basis for calculating the carbon footprint of liquid waste is its annual total volume that is discharged in a given year (expressed in cubic decameters – 1 dam³ = 1,000 m³). The highest result of the generated carbon footprint of liquid waste (given in global hectares [gha]) was attributed to the unit that discharged the most pollution – Warsaw (with a result of 25,342.738 gha). This was followed by Krakow (10,359.796 gha) and Wrocław (8,610.816 gha). The cities with the lowest CFs for this component were Gorzów Wielkopolski, Opole, and Olsztyn (which had results of 1,156.229, 1,613.244, 1,838.447 gha, respectively (Table D1).

Table D1. Carbon footprint of liquid waste for each city

Urban settlement	Population	Liquid waste in total [dam ³]	Liquid waste per capita [dam ³]	CF [gha]	CF per capita [gha]
Wrocław	674,312	36,477.00	0.0541	8610.816	0.013
Bydgoszcz	334,026	18,019.00	0.0539	4253.592	0.013
Toruń	197,112	9067.00	0.0460	2140.370	0.011
Lublin	332,852	17,177.00	0.0516	4054.829	0.012
Zielona Góra	118,011	9382.00	0.0795	2214.729	0.019
Gorzów Wielkopolski	139,667	4898.00	0.0351	1156.229	0.008
Łódź	664,860	36,440.00	0.0548	8602.082	0.013
Krakow	802,583	43,886.00	0.0547	10,359.796	0.013
Warsaw	1,863,056	107,356.50	0.0576	25,342.738	0.014
Opole	126,775	6834.00	0.0539	1613.244	0.013
Rzeszów	196,374	10,069.00	0.0513	2376.903	0.012
Białystok	293,413	13,047.00	0.0445	3079.895	0.010
Gdańsk	486,271	20,111.00	0.0414	4747.433	0.010
Katowice	282,755	14,965.70	0.0529	3532.826	0.012
Kielce	185,478	12,138.00	0.0654	2865.315	0.015
Olsztyn	169,251	7788.00	0.0460	1838.447	0.011
Poznań	545,073	29,737.40	0.0546	7019.856	0.013
Szczecin	394,482	20,113.00	0.0510	4747.905	0.012

Highest values highlighted in gray

Source: own compilation based on GUS 2021 data

The carbon footprint of liquid waste per capita enabled a comparison of the parameters of all of the cities in the study. The units with the highest CFs were Zielona Góra (0.019 gha), Kielce (0.015 gha), and Warsaw (0.014 gha). The cities with the lowest CFs per capita of liquid waste were Gorzów Wielkopolski (0.008 gha), Białystok, Gdańsk (each with 0.010 gha), Toruń, and Olsztyn (0.011 gha each). The remaining urban settlements had results that were within a range of 0.012 to 0.013 gha.

D.2. CF of Solid Waste

Some cities lacked data in fractions such as plastics, metals, and textiles (Table D2); this situation may have been due to their inaccurate waste management, the way their waste management was carried out, or low environmental awareness among their residents. The lack of data in these categories (especially for metals) could have greatly affected the final accounts of the carbon footprint of solid waste due to its high relevance in the calculations of CFs.

Table D2. Carbon footprint of solid waste for each city

Urban settlement	Population	CF [g/ha]							CF per capita
		Mixed	Paper and cardboard	Glass	Composite materials (plastic)	Metals	Textiles	Summary CF	
Wrocław	674,312	48,999.68	6479.70	6271.67	136.60	293.31	19.17	62,200.13	0.092
Bydgoszcz	334,026	10,876.67	1507.21	2020.08	173.20	3171.52	0.00	17,748.68	0.053
Toruń	197,112	8641.75	871.10	865.55	2742.46	14.65	0.00	13,135.50	0.067
Lublin	332,852	11,369.43	1448.01	1697.52	5731.19	0.00	0.00	20,246.15	0.061
Zielona Góra	118,011	5688.63	503.76	489.49	1299.43	5.39	1.12	7987.82	0.068
Gorzów Wlkp.	139,667	8427.93	756.37	697.58	1597.84	271.84	2.54	11,754.10	0.084
Łódź	664,860	30,788.91	2739.31	2010.05	9103.50	59.39	0.34	44,701.49	0.067
Kraków	802,583	41,169.87	4417.32	5471.72	1951.65	1.22	24.01	53,035.79	0.066
Warsaw	1,863,056	90,882.85	6481.09	10,346.67	49.28	415.53	26.84	108,202.26	0.058
Opole	126,775	5115.17	680.75	934.23	92.98	128.54	19.91	6971.58	0.055
Rzeszów	196,374	6,492.13	529.95	1031.25	202.53	0.00	0.81	8256.66	0.042
Białystok	293,413	11,818.68	1558.07	1685.71	1900.68	1605.06	4.67	18,572.87	0.063
Gdańsk	486,271	19,237.68	3139.52	3599.23	4.28	7.91	6.85	25,995.47	0.053
Katowice	282,755	15,316.36	1056.96	1401.27	277.64	0.00	0.00	18,052.23	0.064
Kielce	185,478	10,719.96	818.86	1075.67	17.67	21.09	0.00	12,653.24	0.068
Olsztyn	169,251	6926.58	782.77	809.50	970.46	151.26	17.22	9657.79	0.057
Poznań	545,073	24,042.03	3327.34	3544.22	5627.56	0.25	2.78	36,544.17	0.067
Szczecin	394,482	18,822.69	1568.02	2150.21	0.00	108.17	0.00	22,649.08	0.057

Highest values highlighted in gray

Source: own compilation based on GUS 2021 data

The carbon footprint of solid waste per capita took on low-to-medium values for more than half of the urban settlements. The lowest result was achieved by the city of Rzeszów (0.042 gha); this was followed by Bydgoszcz, Gdańsk (0.053 gha each), Opole (0.055 gha), Szczecin, and Olsztyn (0.057 gha each). Despite having the highest solid waste production, Warsaw had a low CF per capita score (0.058 gha). The cities that generated the most solid waste per capita were Gorzów Wielkopolski (0.084 gha) and Wrocław (0.092 gha); both surpassed Rzeszów's score by more than 100%.

D.3. CF of Water Use

The urban settlements that consumed the most water overall were Warsaw (about 81 million m³), Krakow (about 36 million m³), Wrocław (about 30 million m³), Łódź (about 26 million m³), and Poznań (about 22 million m³). The values of the carbon footprints of the water consumption were at different levels; however, the results were most dependent on the size of the given urban settlement. The smallest city (Zielona Góra) had the lowest carbon footprint value (677.52 global hectares), while the largest city (Warsaw) had the highest CF value (13.908.09 gha) (Table D3).

Table D3. CF of water use for each urban settlement

Urban settlement	Population	Piped water per capita in households [m ³]	Piped water per capita in households in total [m ³]	CF [gha]	CF per capita [gha]
Wrocław	674,312	44.00	29,669,728.00	5115.25	0.0076
Bydgoszcz	334,026	35.40	11,824,520.40	2038.62	0.0061
Toruń	197,112	35.20	6,938,342.40	1196.22	0.0061
Lublin	332,852	33.30	11,083,971.60	1910.95	0.0057
Zielona Góra	118,011	33.30	3,929,766.30	677.52	0.0057
Gorzów Wielkopolski	139,667	34.90	4,874,378.30	840.37	0.0060
Łódź	664,860	39.10	25,996,026.00	4481.88	0.0067
Krakow	802,583	44.40	35,634,685.20	6143.65	0.0077
Warsaw	1,863,056	43.30	80,670,324.80	13,908.09	0.0075
Opole	126,775	42.10	5,337,227.50	920.17	0.0073
Rzeszów	196,374	39.40	7,737,135.60	1333.93	0.0068
Białystok	293,413	34.80	10,210,772.40	1760.40	0.0060
Gdańsk	486,271	40.10	19,499,467.10	3361.84	0.0069
Katowice	282,755	38.60	10,914,343.00	1881.70	0.0067
Kielce	185,478	35.90	6,658,660.20	1148.00	0.0062
Olsztyn	169,251	35.20	5,957,635.20	1027.14	0.0061
Poznań	545,073	40.00	21,802,920.00	3758.97	0.0069
Szczecin	394,482	36.90	14,556,385.80	2509.62	0.0064

Highest values highlighted in gray

Source: own compilation based on GUS 2021 data

The carbon footprint of water consumption per capita ranged from 0.0057 to 0.0077 gha. The cities that generated the smallest carbon footprints from water consumption were Lublin and Zielona Góra (whose CFs were 0.0057 gha). Urban settlements such as Kielce, Szczecin, Olsztyn, Białystok, Bydgoszcz, Toruń, and Gorzów Wielkopolski had average CFs per capita (which ranged from 0.0060 to 0.0064 gha). The units with the highest per capita household carbon footprints were Krakow (0.0077 gha), Wrocław (0.0076 gha), Warsaw (0.0075 gha), and Opole (0.0073 gha) (Table D3).

D.4. CF of Electricity Use

The total electricity use had a very wide range of results, beginning with Gorzów Wielkopolski (116,472,501.31 kWh) and ending with Warsaw (1,979,198,911.04 kWh [17-times higher than GW's score]) (Table D4). The carbon footprints of the electricity use were the greatest for Warsaw (599,590.23 gha), Krakow (249,441.41 gha), and Wrocław (192,946.61 gha). On the other hand, the smallest carbon footprints could be found in Zielona Góra (27,416.69 gha), Opole (34,588.03 gha), and Olsztyn (36,080.93 gha) (Table D4).

Table D4. CF of electricity use for each urban settlement

Urban settlement	Population	Electricity use per capita [kWh]	Electricity use in total [kWh]	CF of electricity use [gha]	CF of electricity use per capita [gha]
Wrocław	674,312	944.52	636,901,170.24	192,946.61	0.286
Bydgoszcz	334,026	712.53	238,003,545.78	72,102.20	0.216
Toruń	197,112	704.30	138,825,981.60	42,056.76	0.213
Lublin	332,852	757.33	252,078,805.16	76,366.24	0.229
Zielona Góra	118,011	766.88	90,500,275.68	27,416.69	0.232
Gorzów Wielkopolski	139,667	833.93	116,472,501.31	35,284.87	0.253
Łódź	664,860	876.98	583,068,922.80	176,638.35	0.266
Krakow	802,583	1025.92	823,385,951.36	249,441.41	0.311
Warsaw	1,863,056	1062.34	1,979,198,911.04	599,590.23	0.322
Opole	126,775	900.59	114,172,297.25	34,588.03	0.273
Rzeszów	196,374	717.25	140,849,251.50	42,669.71	0.217
Białystok	293,413	666.37	195,521,620.81	59,232.48	0.202
Gdańsk	486,271	814.96	396,291,414.16	120,054.87	0.247
Katowice	282,755	935.69	264,571,025.95	80,150.71	0.283
Kielce	185,478	729.00	135,213,462.00	40,962.37	0.221
Olsztyn	169,251	703.69	119,100,236.19	36,080.93	0.213
Poznań	545,073	886.74	483,338,032.02	146,425.28	0.269
Szczecin	394,482	799.35	315,329,186.70	95,527.69	0.242

Highest values highlighted in gray

Source: own compilation based on GUS 2021 data

Most of the cities had proportionally similar CF per capita values of electricity use; these were Białystok (0.202 gha), Toruń, Olsztyn (0.213 gha each), Bydgoszcz (0.216 gha), Kielce (0.221 gha), and Lublin (0.229 gha). Warsaw and Krakow had the highest CF per capita values (0.322 and 0.311 gha, respectively) (Table D4).

D.5. CF of Gas Use

The basis for calculating the carbon footprint for gas consumption was its intake from the gas network per capita per year (in kilowatt-hours). The largest carbon footprint values for gas consumption were held by Warsaw (292,572.70 gha), Wrocław (141,441.38), and Krakow (139,099.12 gha), while the smallest CF values characterized the cities of Zielona Góra (12.216.40 gha), Opole (19,096.89 gha), and Olsztyn (24,018.69 gha). The average carbon footprint value for the cities in the study area was 68,148.01 gha (Table D5).

Table D5. CF of gas use for each urban settlement

Urban settlement	Population	Network gas in households per capita [kWh]	Network gas in households in total [GWh]	CF of gas use [gha]	CF of gas use per capita [gha]
Wrocław	674,312	2430.7	1639.05	141,441.38	0.210
Bydgoszcz	334,026	1437.5	480.16	41,435.48	0.124
Toruń	197,112	1594.3	314.26	27,118.60	0.138
Lublin	332,852	1789.7	595.71	51,406.22	0.154
Zielona Góra	118,011	1199.6	141.57	12,216.40	0.104
Gorzów Wielkopolski	139,667	2239.8	312.83	26,995.25	0.193
Łódź	664,860	1332.0	885.59	76,422.05	0.115
Krakow	802,583	2008.4	1611.91	139,099.12	0.173
Warsaw	1,863,056	1819.8	3390.39	292,572.70	0.157
Opole	126,775	1745.6	221.30	19,096.89	0.151
Rzeszów	196,374	2168.1	425.76	36,740.71	0.187
Białystok	293,413	1491.6	437.65	37,767.30	0.129
Gdańsk	486,271	1388.1	674.99	58,248.31	0.120
Katowice	282,755	1942.9	549.36	47,407.27	0.168
Kielce	185,478	1781.9	330.50	28,520.69	0.154
Olsztyn	169,251	1644.5	278.33	24,018.69	0.142
Poznań	545,073	2129.4	1160.68	100,160.42	0.184
Szczecin	394,482	1938.7	764.78	65,996.67	0.167

Highest values highlighted in gray

Source: own compilation based on GUS 2021 data

High values for the carbon footprint of gas use per capita were quantified for Wrocław (0.210 gha [the highest score]), Gorzów Wielkopolski (0.193 gha), Rzeszów (0.187 gha), and Poznań (0.184 gha). The lowest per capita values could be found in Zielona Góra, Łódź, and Gdansk (0.104, 0.115, and 0.119 gha, respectively). The average CF per capita of the study area was 0.150 gha (Table D5).

D.6. CF of Individual Mobility/Transportation

The carbon footprint was quantified according to fuel type (gasoline, diesel, and propane). The CF represented the smallest values for each fuel type for two cities: Zielona Góra and Gorzów Wielkopolski. The units with the largest amounts of generated total carbon footprints from individual mobility were Warsaw (1,641,705.05 gha) and Krakow (626,490.79 gha) (Table D6).

Table D6. CF of individual mobility for each urban settlement

Urban settlement	CF of individual mobility per fuel type [gha]			CF of individual mobility [gha]	CF of individual mobility per capita [gha]
	CF of gasoline	CF of diesel	CF of LPG		
Wrocław	311,171.69	163,754.26	40,148.15	515,074.10	0.764
Bydgoszcz	165,938.68	64,411.85	31,162.82	261,513.35	0.783
Toruń	81,661.66	39,059.26	16,478.77	137,199.69	0.696
Lublin	130,686.17	72,532.16	39,808.92	243,027.25	0.730
Zielona Góra	54,132.14	32,090.31	9630.91	95,853.35	0.812
Gorzów Wielkopolski	63,453.07	32,702.94	9413.76	105,569.77	0.756
Łódź	298,306.07	117,019.26	84,467.92	499,793.26	0.752
Krakow	396,566.30	161,232.24	68,692.25	626,490.79	0.781
Warsaw	1,037,317.40	474,653.88	129,733.77	1,641,705.05	0.881
Opole	72,862.11	34,269.08	8778.74	115,909.92	0.914
Rzeszów	79,691.99	43,965.06	18,936.68	142,593.72	0.726
Białystok	92,619.16	53,293.94	28,803.51	174,716.61	0.595
Gdańsk	227,237.42	114,634.30	28,792.95	370,664.67	0.762
Katowice	172,200.11	66,701.46	22,732.70	261,634.26	0.925
Kielce	73,813.15	45,892.34	16,175.93	135,881.42	0.733
Olsztyn	70,593.13	35,255.96	13,268.47	119,117.55	0.704
Poznań	317,230.35	141,342.06	30,948.02	489,520.43	0.898
Szczecin	178,617.23	80,327.09	23,080.14	282,024.45	0.715

Highest values highlighted in gray

Source: own compilation based on GUS 2021 data

The carbon footprint of mobility per capita was identified as the largest percentage of the total CF (after summarizing all of the categories). Within this study, individual mobility could be seen as the area with the greatest environmental impact. The cities with the smallest per capita CF values were Białystok (0.595 gha), Toruń (0.696 gha), Olsztyn (0.704 gha), Szczecin (0.715 gha), Rzeszów (0.726 gha), and Lublin (0.730 gha). The lower results were due to the predominance of the more-environmentally-friendly types of fuel that were used in these cities: diesel and propane (Table D6).

D.7. CF of Food Consumption

In all of the food categories, there were small differences in consumption due to the uniform preferences of the urban populations. In those cities with populations of 200,000 or fewer, the consumption of products such as milk, vegetable fats, and sugar was higher than that of cheese. Consumption for poultry ranged from 13.56 to 16.56 kg, milk – 30.36 to 34.44 kg, cheese – 12.12 to 13.92 kg, vegetable fats – 5.52 to 7.08 kg, and sugar – 5.28 to 6.96 kg (Table D7).

Table D7. Annual food consumption per capita in each urban settlement (Part I)

Urban settlement	Population	Beef [kg]	Pork [kg]	Poultry [kg]	Milk [kg]	Cheese [kg]	Vegetable fats [kg]	Sugar [kg]
Wrocław	674,312	2.5	40.8	13.56	30.36	13.92	5.52	5.28
Bydgoszcz	334,026	2.5	40.8	15.6	33.6	13.2	6.72	6.72
Toruń	197,112	2.5	40.8	15.6	33.6	13.2	6.72	6.72
Lublin	332,852	2.5	40.8	15.6	33.6	13.2	6.72	6.72
Zielona Góra	118,011	2.5	40.8	16.56	34.44	12.12	7.08	6.96
Gorzów Wielkopolski	139,667	2.5	40.8	16.56	34.44	12.12	7.08	6.96
Łódź	664,860	2.5	40.8	13.56	30.36	13.92	5.52	5.28
Krakow	802,583	2.5	40.8	13.56	30.36	13.92	5.52	5.28
Warsaw	1,863,056	2.5	40.8	13.56	30.36	13.92	5.52	5.28
Opole	126,775	2.5	40.8	16.56	34.44	12.12	7.08	6.96
Rzeszów	196,374	2.5	40.8	16.56	34.44	12.12	7.08	6.96
Białystok	293,413	2.5	40.8	15.6	33.6	13.2	6.72	6.72
Gdańsk	486,271	2.5	40.8	15.6	33.6	13.2	6.72	6.72
Katowice	282,755	2.5	40.8	15.6	33.6	13.2	6.72	6.72
Kielce	185,478	2.5	40.8	16.56	34.44	12.12	7.08	6.96
Olsztyn	169,251	2.5	40.8	16.56	34.44	12.12	7.08	6.96
Poznań	545,073	2.5	40.8	13.56	30.36	13.92	5.52	5.28
Szczecin	394,482	2.5	40.8	15.6	33.6	13.2	6.72	6.72

Source: own compilation based on GUS 2021 data

In those cities with more than 200,000 inhabitants, there were only two categories where the per capita consumption was higher than in the smaller territorial units: citrus fruits/bananas and apples. Their consumption ranged from 20.76 to 21.24 kg and from 11.28 to 12.72 kg, respectively. The smaller cities with up to 200,000 inhabitants continued to have higher consumption levels in categories such as bread (26.16–32.04 kg), potatoes (21–26.88 kg), and coffee (2.16–2.4 kg) (Table D8).

Table D8. Annual food consumption per capita in each urban settlement (Part II) and CF of food consumption

Urban settlement	Bread [kg]	Potatoes [kg]	Citrus and bananas [kg]	Apples [kg]	Coffee [kg]	Beer obtained from malt [L]	CF of food consumption [gha]	CF of food consumption per capita [gha]
Wrocław	26.16	21.00	21.24	11.88	2.16	92.7	174,568.89	0.259
Bydgoszcz	30.24	26.28	21.12	12.72	2.40	92.7	89,975.55	0.269
Toruń	30.24	26.28	21.12	12.72	2.40	92.7	53,095.45	0.269
Lublin	30.24	26.28	21.12	12.72	2.40	92.7	89,659.32	0.269
Zielona Góra	32.04	26.88	20.76	11.28	2.40	92.7	31,894.53	0.270
Gorzów Wielkopolski	32.04	26.88	20.76	11.28	2.40	92.7	37,747.44	0.270
Łódź	26.16	21.00	21.24	11.88	2.16	92.7	172,121.91	0.259
Krakow	26.16	21.00	21.24	11.88	2.16	92.7	207,776.25	0.259
Warsaw	26.16	21.00	21.24	11.88	2.16	92.7	482,316.22	0.259
Opole	32.04	26.88	20.76	11.28	2.40	92.7	34,263.15	0.270
Rzeszów	32.04	26.88	20.76	11.28	2.40	92.7	53,073.49	0.270
Białystok	30.24	26.28	21.12	12.72	2.40	92.7	79,035.76	0.269
Gdańsk	30.24	26.28	21.12	12.72	2.40	92.7	130,985.32	0.269
Katowice	30.24	26.28	21.12	12.72	2.40	92.7	76,164.84	0.269
Kielce	32.04	26.88	20.76	11.28	2.40	92.7	50,128.66	0.270
Olsztyn	32.04	26.88	20.76	11.28	2.40	92.7	45,743.03	0.270
Poznań	26.16	21.00	21.24	11.88	2.16	92.7	141,110.92	0.259
Szczecin	30.24	26.28	21.12	12.72	2.40	92.7	106,260.40	0.269

Highest values highlighted in gray

Source: own compilation based on GUS 2021 data

The carbon footprint of food per capita was represented by three values; these corresponded to each city's size and its average annual consumption of the particular food items. The small cities (with up to 200,000 residents) had the highest per capita CF score (0.270 gha). Medium-sized units (with populations of 200,000 to 500,000) were characterized by a CF per capita score of 0.269 gha, while the largest agglomerations (exceeding 500,000 people) achieve a CF per capita score of 0.259 gha (Table D8).