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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 $CO_2$ 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].

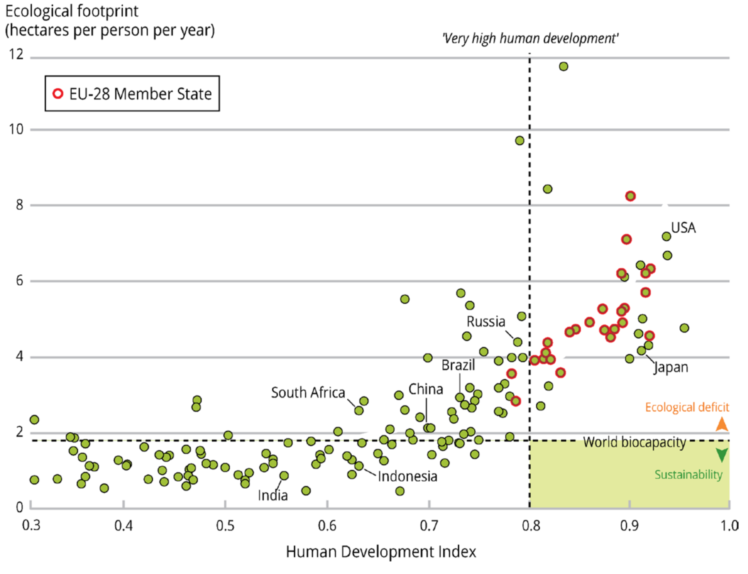


**Fig. 1.** Correlation of EF and HDI; green rectangle represents so-called global sustainable-development quadrant

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].

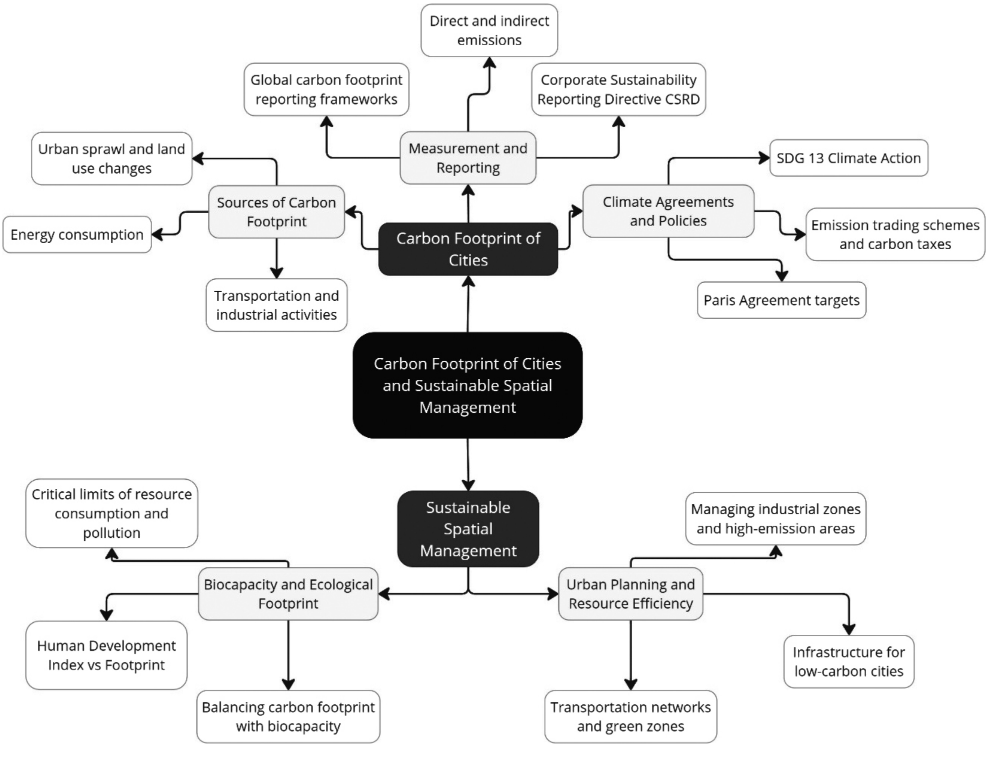


**Fig. 2.** Mind map based on literature review

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).

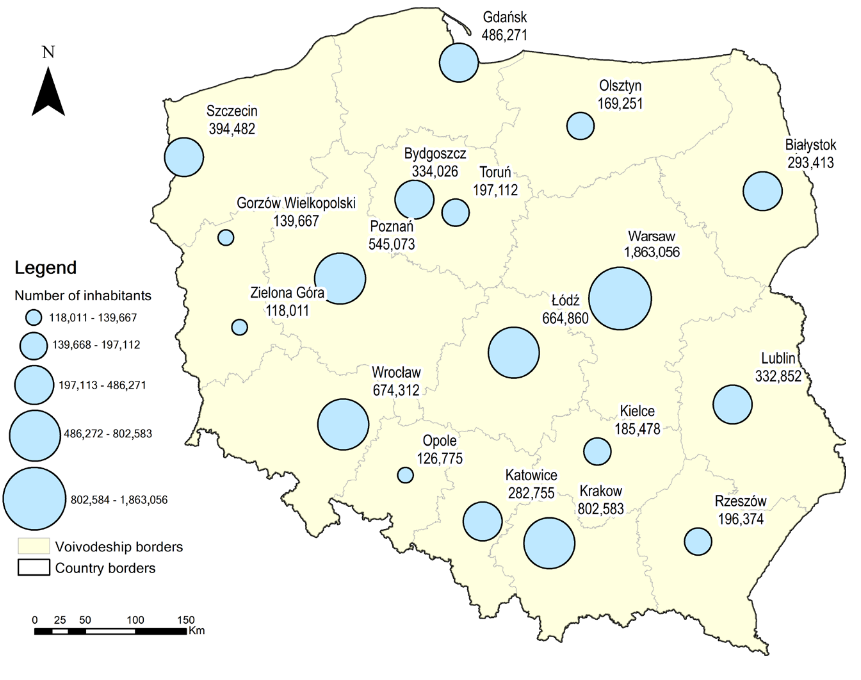


**Fig. 3.** Analyzed cities and their populations
Source: elaboration using QGIS

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 ($CO_2$/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.

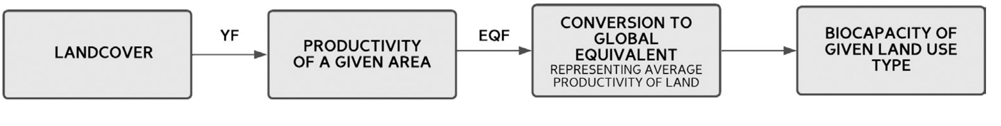


**Fig. 5.** Scheme of biocapacity assessment

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).

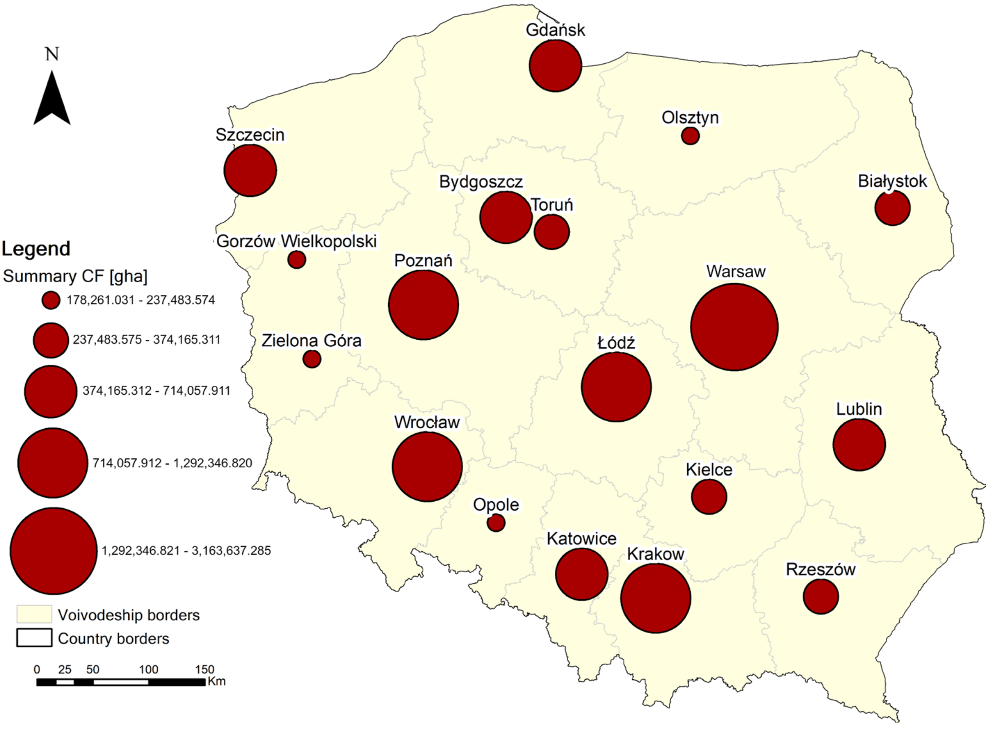


**Fig. 6.** Summary of carbon footprints of study area
Source: elaboration using QGIS

### 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] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Liquid waste | Solid waste | Water | Energy | Gas | Food | Mobility | Total CF | CF per capita |
| 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 |
| Krakow | 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] | | | | | | |
|---|---|---|---|---|---|---|---|
| | Forest lands | Inland and marine fishing grounds | Croplands | Built-up lands/ infrastructures | Grazing lands | Total BC | Total BC per capita |
| 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 |
| Krakow | 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

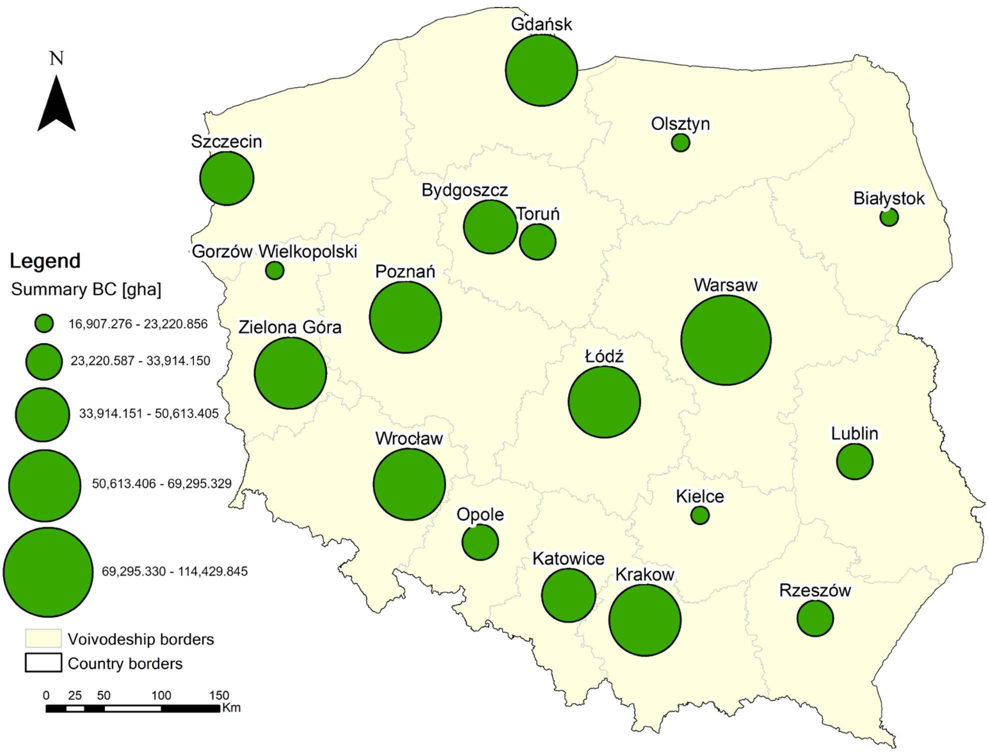


**Fig. 7.** Total biocapacity of study area

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 |
| Krakow | 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 |
| Krakow | 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. Whzen 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.

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## 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:

$$CF_S = I_N \cdot A_S \cdot A_{SEL} \cdot I_{EL_{CO2eq}} \cdot 10^{-3} \cdot EQF \cdot Is_{CO_2} \quad \text{(C.1)}$$

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 [$dam^3$],
$A_{SEL}$ – coefficient of energy required to collect and treat 1 $m^3$ of liquid waste [$kWh/m^3$],
$I_{EL_{CO2eq}}$ – 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 [$gha/tCO_2$].

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.

$$CF_{Gb} = \Sigma\left(A_{Gbn} \cdot I_{Gbn_{CO2eq}} \cdot EQF \cdot Is_{CO_2}\right) \tag{C.2}$$

where:

$CF_{Gb}$ – carbon footprint of garbage generation [gha],
$A_{Gbn}$ – annual amount of given garbage fraction generated from households in given municipality [t],
$I_{Gbn_{CO2eq}}$ – 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:

$$CF_W = I_N \cdot A_W \cdot A_{WEL} \cdot I_{EL_{CO2eq}} \cdot 10^{-6} \cdot EQF \cdot Is_{CO_2} \tag{C.3}$$

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/$m^3$],
$I_{EL_{CO2eq}}$ – 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]:

$$CF_{EL} = I_N \cdot A_{EL} \cdot I_{EL_{CO2eq}} \cdot 10^{-6} \cdot EQF \cdot Is_{CO_2} \tag{C.4}$$

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],
$I_{EL_{CO2eq}}$ – 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]:

$$CF_G = I_N \cdot A_{GkWh} \cdot I_{GkWh} \cdot I_{G_{CO2eq}} \cdot 10^{-3} \cdot EQF \cdot Is_{CO_2} \quad \text{(C.5)}$$

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),
$I_{G_{CO2eq}}$ – total emissions of $CO_2$ in kilograms generated per 1 GJ of gas [kg$CO_2$/GJ],
$EQF$ – equivalence factor for forest land use type [–],
$Is_{CO_2}$ – global carbon dioxide sequestration rate [gha/t$CO_2$].

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):

$$CF_{CU} = \Sigma\left(C_N \cdot A_F \cdot F_F \cdot 10^{-6} \cdot I_{K_{CO2eq}} \cdot EQF \cdot Is_{CO_2}\right) \quad \text{(C.6)}$$

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,

$I_{K_{CO2eq}}$ – average $CO_2$ emissions generated per driven kilometer [t$CO_2$/TJ]:

- gasoline: 73.1,
- diesel: 74.0,
- propane: 65.5,

$EQF$ = 1.2793 [–],
$Is_{CO_2}$ = 0.334 [gha/t$CO_2$].

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:

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

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 $CO_2$ ($CO_2$eq) 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:

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

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 $dam^3$ = 1,000 $m^3$). 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 [dam³] | Liquid waste per capita [dam³] | 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 [gha] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mixed | Paper and cardboard | Glass | Composite materials (plastic) | Metals | Textiles | Summary CF | CF per capita |
| 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 |
| Krakow | 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 $m^3$), Krakow (about 36 million $m^3$), Wrocław (about 30 million $m^3$), Łódź (about 26 million $m^3$), and Poznań (about 22 million $m^3$). 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).