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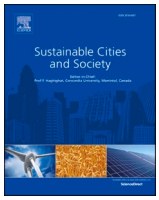

Assessing the sustainability of urbanization at the sub-national level: The Ecological Footprint and Biocapacity accounts of the Budapest Metropolitan Region, Hungary

Zoltán Kovács [a,b,*], Jenő Zsolt Farkas [c], Cecília Szigeti [d,f], Gábor Harangozó [e]

[a] Research Centre for Astronomy and Earth Sciences, Geographical Institute, H-1112 Budapest, Budaörsi út 45, Hungary
[b] University of Szeged, Department of Economic and Social Geography, H-6722 Szeged, Egyetem u. 2, Hungary
[c] Centre for Economic and Regional Studies, Great Plain Research Department, H-6000 Kecskemét, Rakóczi út 3, Hungary
[d] Széchenyi István University, Kautz Gyula Economics Faculty, Department of International and Theoretical Economics, H-9026 Győr, Egyetem tér 1, Hungary
[e] Corvinus University of Budapest, H-1093 Budapest, Fővám tér 8, Hungary
[f] Budapest Business School, Faculty of Finance and Accountancy, CESIBUS, H-1149 Budapest, Buzogány u. 10-12, Hungary

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ABSTRACT

The growing concentration of people and wealth often results in imbalances of resource consumption and carrying capacity, therefore, the sustainability assessment of urbanization can offer an important basis for global sustainable transition. This paper aims to provide an analysis of the environmental sustainability of urbanization in Hungary focusing on the long-term changes of ecological footprint and biocapacity at the sub-national level, with a special attention to the Budapest Metropolitan Region (BMR). During the research a hybrid method considering an input-output model and household consumption data was used for the calculation of regional ecological footprint, whereas biocapacity was measured on the basis of land use data. Findings suggest, that even though the ecological deficit of the country has been gradually decreasing since the early 2000s, due to a shrinking population and increasing biocapacity, the ecological overshoot is still significant in the case of Budapest and its agglomeration (30 fold and 2.4 fold respectively). The unsustainability of the BMR is caused partly by demographic factors (7.6% population growth as opposed to the the 7.7% decrease in the countryside) and partly by rising per capita ecological footprint values (especially in the agglomeration from 2.73 to 2.92 gha/capita), which are not balanced by biocapacity on the supply side. This research concluded that policy makers in ageing societies with a highly centralized urban system like Hungary should launch programmes targeted specifically to primary metropolitan areas to improve environmental efficiency and encourage people to change their consumption behaviour.

1. Introduction

Urban agglomerations as population concentrations are home to high levels of energy and material resource consumption. Hence, they tend to use the "carrying capacity" of ecosystems of their hinterland, contributing above average to climate change, pollution, loss of biodiversity, and land erosion (Ahmed et al., 2020; Akrour et al., 2021; Chen et al., 2021; Kassouri, 2021; Narain, 2009; Shaw et al., 2020). In this respect, cities and urban regions – as hotspots of unsustainability – are a key target in the global quest for sustainability (Acuto et al., 2018; Goodwin et al., 2021) and provide laboratories for policy initiatives aimed at climate change mitigation and a global sustainable transition (Galli et al., 2020; Wachsmuth et al., 2016).

The environmental pillar of sustainable development can be measured by two distinct metrics: Ecological Footprint (EF) and Biocapacity (BC) (Wackernagel & Rees, 1996; Borucke et al., 2013). Decreasing biocapacity (BC), accompanied by growing ecological footprint (EF) and urbanization, is the core environmental challenge that many countries face in the world (Ahmed et al., 2020; Nathaniel, 2020). When the consumption of natural resources and services in a country or a region is greater than the capacity of its ecosystems to supply them, we talk about 'biocapacity deficit' or 'overshoot' (Wackernagel & Beyers, 2019; Rees, 2020). Conversely, when the availability of natural resources and services exceeds the residents' demand, the country or its

* Corresponding author at: Research Centre for Astronomy and Earth Sciences, Geographical Institute, H-1112 Budapest, Budaörsi út 45, Hungary.
E-mail address: zkovacs@iif.hu (Z. Kovács).

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region is said to run a 'biocapacity reserve'. Countries of the world are often classified into these two broad categories, and several studies have dealt with the reasons of biocapacity overshoot or reserves (Ahmed et al., 2020; Lee et al., 2021a; Lin et al., 2018; Toth & Szigeti, 2016). However, urbanization and the concentration of people, jobs and capital often result in large-scale territorial imbalances of consumption and resource use at the sub-national level (Syrovátka, 2020; Świąder et al., 2020). In contrast to national-level ecological footprinting, city or urban region based studies can reveal and explain inequalities between the ecological footprints of different socioeconomic and demographic groups within countries (Lee et al., 2021b). Sustainable development and effective policy making at the sub-national level require an understanding of regional resource base regeneration and its demand on wider geographical areas. The simultaneous assessment of the EF and BC of city regions can help national and local governments to better understand the complexity of sustainable urban development and related challenges, and to formulate policies to decrease the pressure on natural resources (Galli et al., 2020; Lin et al., 2018; Świąder et al., 2020a). Moreover, Wackernagel et al. (2019) suggest that resource security (in terms of the availability of biological resources) plays a major role from competitiveness and development perspectives at different territorial levels. Therefore, national policies aimed at increasing competitiveness should seriously consider resource security at the regional level.

To assess the environmental impacts of urban development and its planning implications this paper aims to analyse the existing relationships between the total and per capita EF and BC in Hungary at the sub-national level, with particular attention to the metropolitan region of Budapest. Budapest is Hungary's primary economic and political core concentrating 18% of the population, more than one third of the national GDP and nearly half of the foreign direct investment arriving in the country (Egedy et al., 2017; Egedy & Ságvári, 2021; Pénzes & Demeter, 2021). In this paper we analyse the sustainability of the Budapest Metropolitan Region (BMR) within Hungary which is defined as the spatial unit of Budapest and 185 surrounding municipalities, concentrating 30% of the country's population (Kovács et al., 2019). The main objective of this paper is the simultaneous assessment of EF and BC between 2003 and 2018 for Hungary with a special focus on the BMR. The analysis can reveal wheather the urban development of the country is progressing in a sustainable manner. Our calculations are based on a refined methodology appropriate to address both EF and BC not only at the national level, but also at smaller geographical scales. The results can be useful for policy makers to address the 'hotspots' responsible for the ecological imbalance at the urban level.

The remaining part of this study is structured as follows. In the next section, a literature review addresses how EF and BC can assess the sustainability of urbanization from an environmental angle. It is followed by an introduction to the research methodology and data collection. A section then follows with the main research results. Finally, we discuss the main findings and the limitations of the methodology, and then conclude our study.

2. Sustainability metrics: ecological footprint and biocapacity at the sub-national level

According to Moldan et al. (2012) environmental sustainability is best defined by focusing on its biogeophysical aspects which means maintaining or improving of the Earths's life supporting systems. The two most commonly used sustainability assessment metrics at global, national or regional scales are Ecological Footprint (EF) and Biocapacity (BC) (Kaur and Garg, 2019). The EF is a quantitative framework for measuring renewable natural resources and ecological services demanded by a population's consumption activities at the national, regional, urban district, or even individual levels (Franco, 2021; Galli et al. 2020; Kovács et al., 2020; Lenk et al., 2021). During ecological footprint calculations two approaches are generally followed. On the one hand, the top-down (or compound) approach is based on the National Footprint Accounts provided by the Global Footprint Network (GFN) disaggregated by smaller geographical areas (Wiedmann et al., 2006). On the other hand, the bottom-up (or component-based) approach uses local data for a sub-national geographical unit to quantify the consumption of the local population, on some (e.g. food, commuting, energy use, etc., see e.g. Świąder et al., 2018; 2020a; or Muñiz et al., 2013) or all components of the ecological footprint (Barrett, 2001). An additional geographical and methodological question of the EF calculation is whether we approach it from the perspective of production or consumption (i.e. should we account the EF of a specific product to the area where it is produced or to the location where it is consumed). In agreement with the arguments of Peters and Hertwich (2008), and Csutora and Vetone Mozner (2014), we follow the latter approach in our calculation, as it seems to better consider the principle of responsibility (as producers tend to satisfy the demand of consumers, and the latter play a key role in the EF of different geographical area).

The interpretation of the interplay between urbanization and ecological footprint is rather ambiguous in the literature. Following the Environmental Kuznets Curve (EKC) theory some authors argue that population and economic growth and subsequent urbanization will increase the pressure on the environment, carbon emission and ecological footprint in the short-run, but above a certain income level technological innovations can accelerate sustainable development and reduce EF (Martínez-Zarzoso & Maruotti 2011; Sarwar & Alsaggaf 2019). Thus, the nexus between urbanization and ecological footprint tends to exhibit an inverted U-shape curve. On the contrary, investigating the ASEAN-4 countries Salman et al. (2022) found that urbanization increases ecological footprints both short-run and long-run, and an inverted U-shaped relationship between urbanization and EF in these countries could not be justified. Similar findings were confirmed by Danish and Wang (2019) for N-11 emerging countries and by Balsalobre-Lorente et al. (2021) studying the energy–income–carbon emissions linkage for the case of Portugal, Italy, Greece and Spain during 1995-2015.

The BC tracks the current and actual productivity of ecosystems considering prevailing technologies and management practices rather than the theoretical productivity of such ecosystems (Goldfinger et al. 2014). Based on a similar classification to EF (Borucke et al., 2013), we distinguish five different land area types (crop, grazing, forest, water and built-up/industrial areas, whereas there is no direct 'supply' for carbon uptaking, but forests are considered for neutralise carbon emissions). Thus, biocapacity may be regarded as a new type of ecological capital; playing a fundamental role in competitiveness and relationships between nations, as well as in the quality of life of their communities (Niccolucci et al., 2012). The area of each land type, expressed in hectares (ha), is converted into biocapacity, expressed in global hectares (gha), by applying two conversion factors: the yield factor (YF), based on the ratio between the local average yield of each land type (Y_n) and the corresponding world average yield (Y_w), and the equivalence factor (EQF), a scaling factor that converts one hectare of world-average land into an equivalent number of global hectares (Wackernagel & Rees, 1996; Wackernagel et al., 2017). YF is a country-specific indicator and is included in the National Footprint Accounts (Lin et al., 2019). Some authors have also used modified yield factors to facilitate comparisons of footprint indicators over time and across regions (Wu et al., 2021). As Yue et al. (2011) argue official statistics on the available area of biologically productive land and water are often inaccurate or missing at smaller territorial scales, therefore, conventional calculation methods of BC can be significantly improved by land-use data derived from high-resolution remote-sensing images (Gulácsi & Kovács, 2020; Oșlobanu & Alexe, 2021).

National Footprint Accounts contain the EF and BC of many countries in the world from 1961 to the latest data year. Each country-year result is calculated using up to 15,000 data points from multiple datasets, so a rigorous quality-assurance process is followed to validate the calculations (data.footprintnetwork.org).

Evaluations of long-term changes in biological capacity and

ecological footprint can be used to analyse the development from a sustainability perspective of a country (Rugani et al., 2014; Khan et al. 2021) or a region (Bi et al. 2020). Rugani et al. (2014) analysed longitudinal time series (1995-2009) to determine the state of natural capital use and estimated the ecological deficit (ED) for Luxembourg. Similarly, Khan et al. (2021) used long-term data (1972-2016) to examine the impact of natural resource abundance, energy consumption and population growth on the ecological footprint and CO_2 emissions in the United States. The research results showed that BC is positively related to EF in the US.

Świąder, et al. (2020a) used the carbon footprint (CF) and biocapacity (BC) indicators in an environmental carrying capacity (ECC) assessment of the designated residential areas around the Polish city, Wrocław. The comparison of the two indicators allowed authors to verify the consumed vs. available resources and to quantify the state of the environment in the urban region. In a similar way, Bi et al. (2020) used the EF and BC metrics from 2000 and 2015 to assess the ecological security status of the Guangdong – Hong Kong – Macao Great Bay region from two perspectives: ecological health and ecological risk.

The two metrics can also be used to establish the relative position of cities (Dong et al. 2021), provinces (Wu et al. 2021), groups of countries (Marti & Puertas, 2020), or even all the countries (Sarkodie, 2021; Wang et al., 2013; Wackernagel et al., 2021; Zambrano-Monserrate et al., 2020) in the world. Studying Tibetan cities, Dong et al. (2021) found that the size of EF varies considerably according to differences in the economic structure, level of development, and population distribution. Lhasa is the only densely populated administrative centre of Tibet, but the land area of Lhasa is small and its resource endowment is insufficient to meet the needs of economic development and daily life. Therefore, Lhasa has become the only city in Tibet where the ecological deficit is increasing. According to Wu et al. (2021), between 2000 and 2016, the ecological deficit in China peaked in 2015 (1.85 global hectares per capita). While in 2000, ten provinces still had an ecological surplus, by 2016 all Chinese provinces already had an ecological deficit. Marti and Puertas (2020), calculated the environmental efficiency of 45 African countries, taking into account EF and country size as determinants of production level. They analysed the longitudinal changes of EF and BC by using ordinary least square estimation to identify possible trends in the two variables and on this basis to determine the most appropriate environmental policies to adopt. It was concluded that even countries with a deficit in BC but a level of resource consumption commensurate with their production volume should introduce technological improvements that promote sustainable economic development by helping them to adapt to their existing BC.

According to Sarkodie (2021), increasing the BC of nations will improve ecological performance. His research covered 188 countries throughout 1961-2016 and confirmed the assumption that there is environmental convergence across nations – which means that carbon emissions and ecological footprint differences converge between higher and lower income countries in the long run. This tendency may be driven by (i) the economic catch-up of the developing countries, but also by (ii) the outsourcing of carbon and resource intensive activities from core countries into less-developed ones. Research findings suggest that long-term environmental convergence is possible.

Zambrano-Monserrate et al. (2020) analysed the EF and its determinants, considering the impact of neighbouring countries. During the research, the spatial correlations of the ecological footprint of 158 countries were examined, based on GFN and World Bank data series for 2007-2016. The paper also estimated the direct, indirect and aggregate impacts of biocapacity, trade openness and GDP on the ecological footprint in the short and long term. Their results show that biocapacity, trade openness, and GDP increase countries' ecological footprint, whereas biocapacity shows significant indirect effects in the short and long term. In a similary vein, Danish et al. (2019) studied the relationship between economic growth, biocapacity and the ecological footprint in Pakistan. Their empirical analysis showed that economic growth has positive impact on the ecological footprint and that biocapacity has a positive and significant relationship with the ecological footprint, suggesting that available resources are not sufficient to absorb pollution and improve Pakistan's ecological footprint (Danish et al. 2019). Analysing the ecological deficit and GDP per capita simultaneously Wackernagel et al. (2021) concluded that more and more people live in countries with both a biocapacity deficit and below average (USD 10,000 per capita) income. Low incomes reduce countries' ability to compete on the world market for the resources they need. This trend undermines sustainable development and eliminates the chance of eradicating poverty, which they call the "ecological poverty trap".

Analysing and comparing ecological efficiency and sustainability of countries Gabbi et al. (2021) elaborated a complex indicator using the EF-BC gap. Their biocapacity-adjusted economic growth (BAG) indicator can be used to categorise countries according to whether their economic growth is in line with the principles of sustainability. Two indicators are combined; one is the output gap, a measure of an economy's productive capacity based on the difference between actual and potential GDP, expressed as a percentage of potential GDP. The other is the difference between a country's ecological footprint and biocapacity, which shows the extent to which a country operates within or beyond its ecological limits. A growing body of literature indicates the need for the simultaneous use of EF and BC calculations in sustainability assessments. This is also the primary aim of this paper which tries to link the approach with the study of urbanization and its environmental effects at the sub-national level.

3. Data and methods

In this research, regional EF and BC calculations were carried out for different geographical units of Hungary for the years 2003, 2013, and 2018. The calculations were performed for the following territorial units: the capital city of Budapest, the agglomeration of Budapest (comprising 185 neighbouring municipalities), the Budapest Metropolitan Region (as the sum of Budapest and its agglomeration), the rest of Hungary (excluding the Budapest Metropolitan Region), and Hungary as a country.

3.1. Overview of Ecological Footprint accounting

In our calculations, we quantified the EF from a consumption-based perspective, arguing that this approach is better for grasping the territorial concentration of EF than the production-based one. Furthermore, we only focused on household consumption and disregarded the EF related to governmental and non-governmental spending (similar to Baabou et al., 2017). Firstly, because residential consumption seems to be the best indicator for the geographical distribution of the EF (especially at lower geographical scales), as governmental and non-governmental spendings are highly concentrated to the capital city of Budapest, however, most of their impacts appear elsewhere in the country. Secondly, because residential consumption is responsible for the biggest part (ca. two-thirds) of the EF (see e.g. Wiedmann et al., 2006), see details later in the results section. In this way, our EF calculation is an underestimation of the overall national EF, as it considers only one (although largest) part of it. The calculation addressed two aspects, following the spirit of a hybrid EF calculation approach (see Weinzettel et al., 2014). One direction was to calculate the indirect footprint related to the consumption of households. That part covered the impacts of goods and services throughout the supply chains (including their production, transportation, etc.). The other part was the direct footprint of the goods and services consumed (including carbon releases directly linked to households – e.g. heating and vehicle use).

The indirect part of the household consumption-level footprint was quantified through an input-output model, supported with environmental data (environmentally extended input-output analysis, EEIO), that can also be applied at different geographical scales (Moore et al.,

2013). Input-output models themselves (following the concept of Leontief, 1936) focus on the links between various sectors of the economy unveiling the resource need of them per unit of output in another. The roots of EEIO-based EF calculations go back to Bicknell et al. (1998) and Ferng (2001). This method was supported by the approach of Wiedmann et al. (2006) applied for our sample area.

The indirect footprint part for the household consumption was quantified as follows:

$$EF = EF_{dir} * (I - A)^{-1} * FD \quad (1)$$

where EF_{dir} means the direct intensity matrix, showing the ecological footprint per monetized economic performance of different industrial sectors. The second part, $(I\text{-}A)^{-1}$ is the Leontief-inverse matrix –calculated based on the country-level, 64*64 industry-industry input-output matrix (I) and the intermediate consumption matrix (A)- and lastly, FD means the final demand of households for the output of different industries. The data was accessed from the GFN for the vector EF_{dir}, while the Hungarian Central Statistical Office provided the household level consumption data for our sample area. We decided to use the dataset for 2003 and 2013 (before and after the financial crisis) and 2018 (the latest fully available dataset).

Another part of the household level footprint is directly linked to heating and fuel use (direct carbon footprint part):

- Direct carbon-dioxide emissions and, thus, ecological footprint is in line with burning natural gas and firewood for heating (coal and heating oil are not used anymore for heating) and liquid fuels for transportation. However, this part does not cover the releases from electric heating or vehicles, but the first part already addressed it based on the input-output model.
- The element of built-up areas covered by housing and road infrastructure.

For calculating the direct element of the footprint, the basis was again the final demand vector for different fuels. Then, by using average statistical prices for the respective years, quantities emerged. Finally, by using equivalent factors (heating values, emission factors, area coefficients) all these data could be translated into an ecological footprint component (in global hectares). However, as the built-in part could not be quantified, this calculation is considered an underestimation of the direct footprint component. On the whole, this method is based on the GFN approach, but can also be applied at smaller geographical scales (if the specific consumption data are available).

3.2. Calculation of biocapacity

This study uses both GFN data and own calculations for the analysis and assessment of the temporal changes of biocapacity. The methodology applied to calculate the biocapacity of the subnational territorial units follows the work of Galli et al. (2020). Accordingly, the biocapacity of a region can be derived from data of five land use categories: cropland, grazing land, forest, water, and built-up/infrastructure area. The spatial location and area of these categories were determined by Corine Land Cover data (CLC) (EU, 2021), but as demonstrated by Świąder et al. (2020b) traditional land use maps can also provide sufficient information.. We used CLC 2000 for the year 2003, 2012 for 2013, and 2018 for 2017. Similar longitudinal approach was followed by Geng et al. (2014). The 44 land cover categories of CLC had to be matched to the 5 categories used in our analysis to perform the necessary calculations. In this step, we deviated from the Portuguese case study by Galli et al. (2020) because some natural and semi-natural areas (CLC code numbers 321, 333, 411, and 412) were not considered in their assessment, and we followed rather the approach of Horshburgh et al. (2022). Therefore, we included these grassland areas in the grazing land category, while the transitional woodland-shrub areas (code 324) were counted in the forest category (see Annex 1. for full details). There are several reasons for these modifications: (1) although CLC is a standardized European database, minor methodological differences can be found between the member states; (2) the use of land cover categories differs between the countries. In Hungary, in most cases, the transitional woodland-shrub areas indicate the two endpoints of forest management, i.e. either newly planted forests, or the post-cut state. The 321, 333, 411, and 412 categories are nature conservation areas in Hungary where agricultural use is carried out for nature conservation (typically livestock grazing), so their inclusion is vital when adapting the method to Hungarian conditions.

Land use categories' mean net primary production (NPP) was determined by processing MOD17A3HGF raster data (Running & Zhao, 2019). In the first step, the mean NPP values were determined for three land use types (cropland, grazing land, and forest) and every region in ArcGIS with the zonal statistics function. Based on these and with the GFN country yield factor data (GFN, 2019), the regional yield factor for the three land use categories and every region was calculated using the following formula (Galli et al., 2020).

$$YF_{regionalLU} = \frac{Mean\ NPP_{region}}{Mean\ NPP_{Hungary}} \times YF_{Hungary}$$

$YF_{regionalLU}$ – regional yield factor for given land use

Mean NPP_{region} – regional mean NPP for given land use (kgC/m^2/year)

Mean $NPP_{Hungary}$ – mean NPP for given land use in Hungary (kgC/m^2/year)

$YF_{Hungary}$ – yield factor for given land use of Hungary

The yield factor for built-up areas is the same as for cropland, while for water surfaces it is 1.

The regional biocapacity for given land use was calculated in the next step using the formula below. The area data were derived from Corine Land Cover and the EQF calculation factor came from GFN.

$$BC_{regionalLU} = A_{LU} \times YF_{regionalLU} \times EQF_{LU}$$

$BC_{regionalLU}$ – biocapacity of given land use in a region (gha)

A_{LU} – area of given land use in a region (ha)

$YF_{regionalLU}$ – yield factor of given land use in a region (ha)

EQF_{LU}- equivalence factor of given land use (ha)

Finally, the total biocapacity of a region is the sum of the biocapacity of different regional land uses.

In this study, the overall biocapacity of Hungary and the BMR was calculated for 2017. Due to lack of YF data we could not rely on the most recent CLC dataset from 2018. In addition, our biocapacity calculations for 2017 became also comparable with the latest data reported by GFN.

4. Results and discussion

This study investigates the relationship between urbanization and the long-term (2003-2018) changes of Ecological Footprint (EF) and Biocapacity (BC) in Hungary at the subnational level both in absolute and relative terms. The key questions here to discuss are: How has the EF of the Budapest Metropolitan Region changed over time compared to the rest of the country? Which consumption categories put the greatest pressure on the ecosystems in the BMR? What are the main drivers of the EF in the compact city and in the agglomeration, respectively? Finally, how has the biocapacity of the BMR changed in the investigated period compared to the rest of the country?

4.1. Changes of the household consumption-based Ecological Footprint (EF) and the Biocapacity (BC) over time

As explained in the methodological section, using a bottom-up approach we calculated the EF of Hungary and the BMR based on household consumption data, disregarding the institutional

(governmental and civil) sector. Although the officially published GFN data are the results of a top-down approach where activities of the institutional sector are also considered our EF values show many similarities with those of the GFN and reflect the long-term trends. The household consumption-based EF values get closer to the GFN values (2003 – 65%, 2013 – 69.5%, 2018 – 70.9%) which also shows the growing weight of household consumption in the total ecological footprint of the country in general.

The temporal changes of total EF values between 2003 and 2018 confirm basic differences between the metropolitan region of Budapest and the rest of the country. The total EF value of Budapest's region has steadily increased in the investigated period, while in the rest of Hungary it first declined between 2003 and 2013, then increased between 2013 and 2018 (Table 1). The decrease was mainly the result of the global economic crisis of 2008-2009 and the concomitant decline of consumption, which did not seem to affect Budapest and its metropolitan region. Changes in the absolute values of EF at the regional level are the consequence of two factors, that need to be considered when interpreting the results. Firstly, the population shift within the country (see Table 1), secondly, the changes of per capita values (Table 2). Considering these two factors, we can say that the growing population and increasing per capita consumption have resulted in growing absolute EF values in the BMR between 2003 and 2018, especially in the agglomeration zone. In the rest of Hungary, however, relatively stable absolute EF values were accompanied by a shrinking population. As a consequence, the share of the BMR in Hungary's total ecological footprint increased from 28.3% to 31.5% between 2003 and 2018. At the same time, the Biocapacity (BC) has steadily grown according to the GFN, due to the modernization of agricultural practices and greater agro-efficiency.

Comparing EF and BC data at different geographical levels, a robust – although slightly decreasing – overshoot could be observed for Budapest (from 38 to 32 times according to GFN and from 34 to 30 times according to our data on BC), while the overshoot increased in the zone of agglomeration from 2.1 to 2.4 times. In contrast, according to our calculations the rest of Hungary has "ecological reserves", which increased from 13% to 24% between 2003 and 2018. This can be linked both with population shrinkage (from 7.4 in 2003 to 6.8 million in 2018) and the improving efficiency of agricultural production. At the same time, a modest population growth (caused by migration) coupled with growing levels of income and consumption resulted in an increase of overshoot in the Budapest Metropolitan Region in general. However, we must note that this study focuses on the EF related to household consumption only, so what we present here is likely an underestimation of the overshoot values.

The per capita values of EF at the national level decreased between 2003 and 2013 mainly due to the global financial crisis, and they increased again between 2013 and 2018 due to economic recovery. The changes in the per capita EF values explain another tendency supplementing the impact of population change shown in Table 1. This value has steadily increased in the BMR and especially in the agglomeration zone. In Budapest, the growth of per capita EF was smaller (Table 2), see explanation also later. Data confirm a constant gap between the BMR and the rest of Hungary, resulting from the high concentration of wealth and consumption within the country (Pénzes & Demeter, 2021). Difference also occurs within the BMR, where the per capita EF value of Budapest remained the same between 2013 and 2018, while the value of the agglomeration dynamically grew. This is the result of the spatial shift of affluence, the outflow of high-income groups from the core city to the suburbs with higher levels of consumption (Kok & Kovács, 1999; Kovács & Tosics, 2014). We assume that the EF values of both Budapest and the BMR hide robust spatial differences, however, our dataset does not allow finer spatial resolution. The per capita values of BC increased at the national level and stagnated in the BMR, which is the result of a slight growth in the city itself and a decrease in the agglomeration after 2013. This phenomenon will be further investigated later.

Table 1
Household consumption-based Ecological Footprint (EF) and Biocapacity (BC) data in absolute terms for Budapest Metropolitan Region (BMR) and Hungary, (2003, 2013, 2017-2018).

	Area (1000 ha)	Population change (%, 2003-2018)	EF total* (1000 gha)			BC total** (1000 gha)			Overshoot** (EF/BC)			BC*** total (1000 gha)			Overshoot (EF/BC**)		
			2003	2013	2018	2003	2013	2017	2003	2013	2018	2003	2013	2017	2003	2013	2018
Budapest	52.5	2.75	4210	4399	4423	110	130	138	38.19	33.97	32.54	124	142	147	33.95	30.98	30.08
Agglomeration	557.6	15.4	2877	3226	3546	1170	1375	1462	2.47	2.36	2.47	1336	1463	1470	2.15	2.21	2.41
BMR	610.1	7.58	7087	7625	7969	1280	1504	1600	5.54	5.07	4.98	1460	1605	1617	4.85	4.75	4.92
Rest of Hungary	8692.9	-7.77	17922	14980	17351	18245	21435	22800	0.98	0.70	0.76	20575	22698	22590	0.87	0.66	0.76
Hungary	9303.0	-3.59	25009	22605	25320	19525	22939	24400	1.28	0.99	1.05	22035	24303	24207	1.13	0.93	1.04

Sources:
* own calculations based on household consumption
** based on GFN data
*** own calculation

Table 2
Household consumption-based Ecological Footprint (EC) and Biocapacity (BC) data in per capita terms for the Budapest Metropolitan Region (BMR) and Hungary, (2003, 2013, 2017-2018).

	EF* per capita (gha)			BC** per capita (gha)			BC*** per capita (gha)		
	2003	2013	2018	2003	2013	2017	2003	2013	2017
Budapest	2.47	2.52	2.52	0.065	0.074	0.079	0.073	0.082	0.084
Agglomeration	2.73	2.79	2.92	1.11	1.19	1.20	1.27	1.27	1.23
BMR	2.56	2.63	2.69	0.46	0.52	0.54	0.53	0.55	0.55
Rest of Hungary	2.42	2.10	2.55	2.47	3.02	3.35	2.79	3.20	3.31
Hungary	2.47	2.26	2.59	1.93	2.30	2.50	2.17	2.43	2.47

Sources:
* own calculations based on household consumption
** GFN data
*** own calculations

4.2. Changes of Ecological Footprint (EF)

If we consider different sub-categories of EF by land use, the three most important categories are carbon, cropland, and forest footprint (in this order, for all spatial categories in all three years) (Table 3). These three sub-categories are responsible for around 95% of the total ecological footprint. Between 2003 and 2018, the share of the carbon footprint decreased somewhat, while the cropland and forest footprints increased slightly for Budapest. For the agglomeration, all main components increased slightly. The changes of the different components of EF are in line with the processes explained earlier (shifts in population and per capita values), the only exception seems to be the carbon footprint element. As explained in the methods section, our calculation covers both the indirect (embedded in the life cycle of products and services) and direct components of household consumption related EF. The major difference between Budapest and the agglomeration was the evolution of the direct EF (carbon) component over time. Direct carbon releases through the use of liquid fossil fuels (gasoline and diesel) tended to increase for both spatial units, while the biggest component, the heating related direct carbon footprint component remained around the same for Budapest (owing to energy efficiency improvements in the residential buildings), but increased significantly in the agglomeration (increasing area of buildings and the proliferation of poor carbon efficient firewood heating).

So far, differences in the absolute EF values and changes of the relative EF values by different geographical units have been analyzed. However, the structure of the indirect (embedded) EF component caused by differences in affluence and consumption is also an essential factor. Table 4 provides an overview of the different footprint components based on COICOP (Classification of Individual Consumption by Purpose) consumption categories (UN, 2011) for different spatial units in the investigated period (to enhance the readability of the table, only 2018 and the changes between 2003 and 2018 are shown here).

At the national level, the most significant contributors to the EF are expenditures for food and beverages, housing related energy use, transportation, alcohol, and tobacco in 2018, both regarding absolute and per capita EF values. These four groups of products are responsible for about 79% of the indirect EF. The share of services is much lower. The unexpectedly low EF results for health care and education can be explained by the approach of this research: only household consumption is considered, while governmental and civil sector activity is not covered.

At the BMR level, not only the per capita values are higher in the agglomeration than in Budapest (2.92 versus 2.52 gha/capita respectively), but also their structure is considerably different. On the one hand, the lifestyle and consumption of residents in the agglomeration can be characterised by slightly higher food, household energy (as a consequence of bigger dwelling sizes), and transport (because of the higher commuting need, see Kovács et al. 2017) related EF. On the other hand, although the above mentioned EF categories are also important for Budapest, services like dining out, accommodation, healthcare, entertainment and culture, including domestic tourism etc. accounted for a higher value in 2018, most probably also due to the higher income levels.

Looking at temporal changes, there seem to be no significant differences between per capita EF values between 2003 and 2018 (so, again, changes in absolute values are mainly the consequence of spatial population changes). However, the EF values of some consumption categories (e.g. food, transportation, and restaurant/hotel expenditures) have increased, most probably because of the increasing income levels. The per capita household energy related EF only increased in the agglomeration (indicating the growing size of residential buildings) while decreased elsewhere. Interestingly, the EF of clothing is also low, the negative impacts of this sector rather emerge in the output (waste) side, rather than the resource use (EF) side. It further decreased between 2003 and 2018. In our understanding, it is likely the result of the "plastification" of the fashion industry, as plastic has lower resource needs (EF) than cotton.

Repeatedly, we must note that EF values along with different consumption categories only cover the indirect - embedded in the life-cycle of the products - EF component. The heating-related part could be allocated to COICOP category 04. The fuel consumption related part, however, cannot precisely be split between categories 07 and 09. Thus, the data presented in Table 4 provide very likely an underestimation of

Table 3
Per capita Ecological Footprint by land use categories (2003, 2013, 2018).

	Budapest (gha/capita)			Agglomeration (gha/capita)			Hungary (gha/capita)		
	2003	2013	2018	2003	2013	2018	2003	2013	2018
Crop	0.89	0.93	0.97	0.95	0.9	0.99	0.84	0.7	0.91
Grazing	0.059	0.062	0.064	0.063	0.060	0.065	0.056	0.046	0.061
Forest	0.24	0.35	0.30	0.26	0.36	0.32	0.22	0.31	0.29
Fish	0.018	0.021	0.019	0.017	0.014	0.016	0.014	0.017	0.016
Built-up	0.038	0.039	0.031	0.036	0.034	0.027	0.032	0.030	0.027
Carbon	1.22	1.11	1.15	1.41	1.41	1.51	1.29	1.16	1.29
Total	2.47	2.52	2.52	2.73	2.79	2.92	2.47	2.26	2.59

Sources: own calculations.

Table 4
Indirect* Ecological Footprint of household consumption by consumption categories (COICOP) in 2018 and for 2018/2003.

			01 - Food and beverages	02 - Alcohol. tobacco and narcotics	03 - Clothing and footwear	04 - Housing, water, electricity, gas, fuels	05 - Furnishings, household equipment	06 - Health	07 - Transport	08 - Communication	09 - Recreation and culture	10 - Education	11 - Restaurants and hotels	12 - Miscellaneous goods/ services	TOTAL
Budapest	**gha**	2018	1 677 375	327 022	57 523	366 990	118 446	64 638	384 326	29 994	177 148	10 954	342 142	82 639	**3 639 196**
		2018/ 2003	*1.09*	*1.04*	*0.64*	*0.90*	*0.70*	*0.99*	*1.20*	*0.69*	*0.58*	*0.81*	*1.29*	*0.83*	***1.00***
	gha/ cap	2018	0.96	0.19	0.03	0.21	0.07	0.04	0.22	0.02	0.10	0.01	0.20	0.05	**2.08**
		2018/ 2003	*1.06*	*1.01*	*0.63*	*0.88*	*0.68*	*0.96*	*1.17*	*0.67*	*0.57*	*0.79*	*1.26*	*0.81*	***0.98***
Agglomeration	**gha**	2018	1 304 855	209 565	32 375	326 658	65 923	32 316	277 215	19 200	85 365	4702	156 186	51 622	**2 565 982**
		2018/ 2003	*1.18*	*1.13*	*0.64*	*1.27*	*0.63*	*1.07*	*1.21*	*0.79*	*0.57*	*0.72*	*1.49*	*0.99*	***1.11***
	gha/ cap	2018	1.07	0.17	0.03	0.27	0.05	0.03	0.23	0.02	0.07	0.00	0.13	0.04	**2.11**
		2018/ 2003	*1.02*	*0.98*	*0.55*	*1.10*	*0.55*	*0.92*	*1.05*	*0.69*	*0.50*	*0.63*	*1.29*	*0.86*	***0.97***
BMR total	**gha**	2018	2 982 230	536 587	89 898	693 648	184 368	96 954	661 541	49 194	262 513	15 656	498 328	134 261	**6 205 179**
		2018/ 2003	*1.13*	*1.08*	*0.64*	*1.05*	*0.68*	*1.02*	*1.20*	*0.72*	*0.58*	*0.78*	*1.35*	*0.89*	***1.05***
	gha/ cap	2018	1.00	0.18	0.03	0.23	0.06	0.03	0.22	0.02	0.09	0.01	0.17	0.05	**2.09**
		2018/ 2003	*1.05*	*1.00*	*0.60*	*0.97*	*0.63*	*0.94*	*1.12*	*0.67*	*0.54*	*0.73*	*1.25*	*0.82*	***0.97***
Rest of Hungary	**gha**	2018	6 219 041	1 100 179	232 217	1 571 148	383 983	130 741	1 410 823	94 989	490 726	28 812	906 530	280 945	**12 850 135**
		2018/ 2003	*1.11*	*0.80*	*0.92*	*0.64*	*1.05*	*0.55*	*0.80*	*0.60*	*0.76*	*1.01*	*1.73*	*0.76*	***0.93***
	gha/ cap	2018	0.91	0.16	0.03	0.23	0.06	0.02	0.21	0.01	0.07	0.00	0.13	0.04	**1.89**
		2018/ 2003	*1.20*	*0.86*	*1.00*	*0.70*	*1.14*	*0.60*	*0.86*	*0.66*	*0.82*	*1.10*	*1.88*	*0.82*	***1.01***
Hungary total	**gha**	2018	9 201 270	1 636 767	322 115	2 264 796	568 352	227 695	2 072 365	144 183	753 240	44 468	1 404 858	415 206	**19 055314**
		2018/ 2003	*1.12*	*0.87*	*0.82*	*0.73*	*0.89*	*0.69*	*0.89*	*0.64*	*0.69*	*0.92*	*1.57*	*0.79*	***0.97***
	gha/ cap	2018	0.94	0.17	0.03	0.23	0.06	0.02	0.21	0.01	0.08	0.00	0.14	0.04	**1.95**
		2018/ 2003	*1.16*	*0.90*	*0.85*	*0.76*	*0.92*	*0.71*	*0.93*	*0.66*	*0.71*	*0.95*	*1.63*	*0.82*	***1.00***

* embedded in supply chains of products.

the EF values of the respective consumption categories.

The comparison of EF of different cities across countries is hampered by differences in approaches (top-down, bottom-up or hybrid), data availability and assumptions within the calculation. Each approach has advantages and disadvantages: the top-down approach is easy and enables comparisons with other countries and cities, however, it fades the role of local consitions. The bottom-up assessment of EF is more accurate and relevant for policy formulations at the local level, however, it has higher burdens both in time and money (Świąder, 2020b). Using a top-down approach to track the EF of 19 coastal cities in the Mediterranean region Baabou et al. (2017) found that the urban region of Tel Aviv accounted for 43% of Israel's entire Ecological Footprint, Athens for 39% and Tirana for 27% of the Greek and Albanian eco-footprint respectively in 2010. The share of BMR in Hungary's bottom-up EF value was 31.5% in 2018, which is similar to the aforementioned cities/countries. This implies that in countries with primate-cities the resource consumption will concentrate in single locations and will impact the countries resource consumption the most. Thus, the urbanization structure of a country very much matters regarding sustainability and adjoining policy prespectives.

Moore et al. (2013) applied a bottom-up approach in the calculation of the EF of Vancouver, a metropolitan region in North America. Authors found that the three largest components of the EF were 'Food', 'Transportation' and 'Housing', which is consistent with our results. Even though authors did not differentiate between the core-city and the agglomeration, the EF data of BMR facilitates certain comparison. In both metropolitan regions the 'Food' component was far the largest, accounting for 45% of Metro Vancouver and 48% of BMR ecological footprint. It was followed by 'Housing' (11.2%) and 'Transportation' (10.6%) in Budapest, whereas in Vancouver share of 'Transportation' (23%) was well above 'Housing' (18%). This can be explained by higher mobility rates and greater reliance on private motor vehicles in Metro Vancouver.

4.3. Changes of Biocapacity (BC)

First, the consistency between the GFN data and our calculations should be examined. Comparing the results at the national level, the largest deviation is 12.8% in 2003, 5.9% in 2013, and only -0.79% in 2017. If we calculate the BC for sub-national territorial units from the GFN dataset using the land area and compare the results with our own calculations, the deviations are between 12.7% and 14.2% in 2003, 5.9% and 9.2% in 2013, and -0.9% to 6.5% in 2017, so clearly a decreasing trend can be observed. The values of Budapest are the most divergent in all three years. Generally, we found that GFN data moderately underestimate the biocapacity of the country and the studied sub-regions, which implies that an area-based measurement of biocapacity is very usefuld when it comes to the assessment of the ecological deficit or reserves of sub-national territorial units, especially urbanized areas.

Both GFN data and our calculations show that national biocapacity values vary from year to year depending on weather conditions and other factors. Therefore, it is difficult to draw general conclusions on data from three years. Therefore, we also made calculations on the long-term changes of biocapacity in Hungary and the BMR between 2000 and 2017, both in absolute and relative terms. Disregarding annual fluctuations, the results show opposite trends in the long-term changes of biocapacity in the BMR and Hungary (Fig. 1A). Generally, the total biocapacity value of Hungary has been growing since the beginning of the millennium due to the intensification and growing efficiency of the agricultural sector (Baráth & Fertő, 2015; Csatári et al., 2019; Lennert & Farkas, 2020). For instance, as part of the modernization process the use of fertilizer per hectare doubled between 2000 and 2017 (from 61 to 123 kg/ha) (KSH, 2021). In contrast with the national trends, a slight

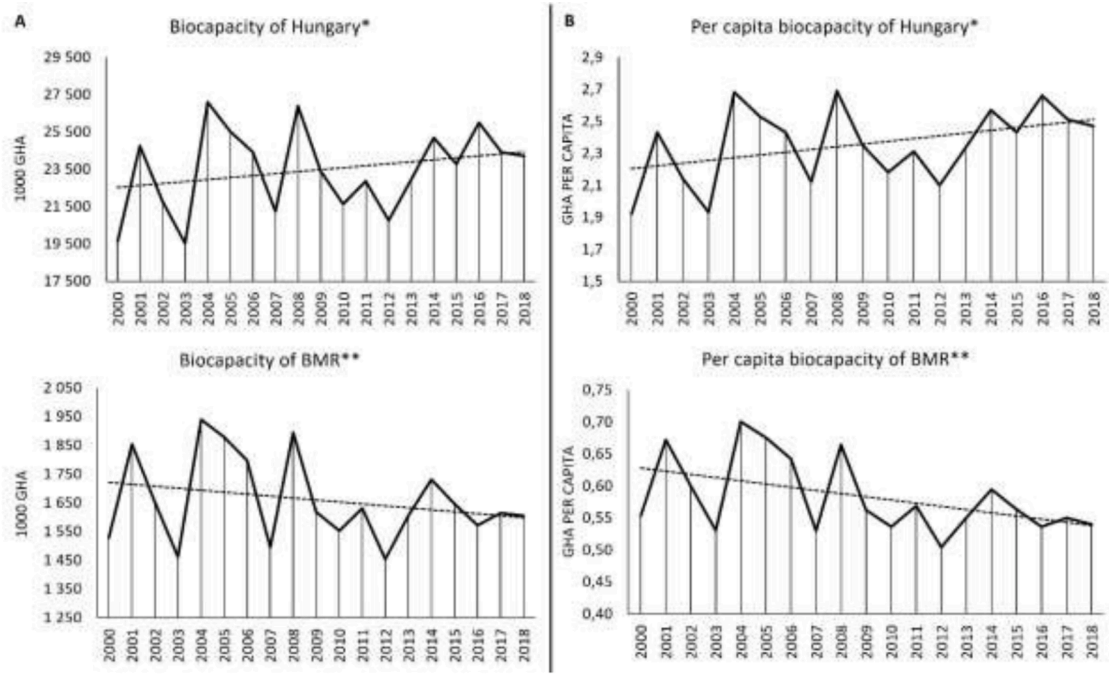


Fig. 1. Biocapacity in absolute and per capita terms in Hungary and in the Budapest Metropolitan Region (2000-2017). Sources: *GFN **own calculations.

decrease in biocapacity can be observed in the Budapest Metropolitan Region which can be linked with the degradation of environmental quality, the shrinkage of biologically active surfaces caused by urbanization, and urban sprawl (Kovács et al., 2019).

Per capita biocapacity values of the country and the BMR show even more marked differences due to demographic and mobility factors. While the population of Hungary decreased by 499 thousand (-4.8%) between 2000 and 2017, that of the BMR increased by 189 thousand (i.e. 6.8%). In the first case, the natural population decrease, in the second case migration played a very important role. Budapest and its surroundings (as the dominant economic pole of the country with income levels well above the national average) served as a magnet for masses of qualified labour and young families (Egedy & Ságvári, 2021).

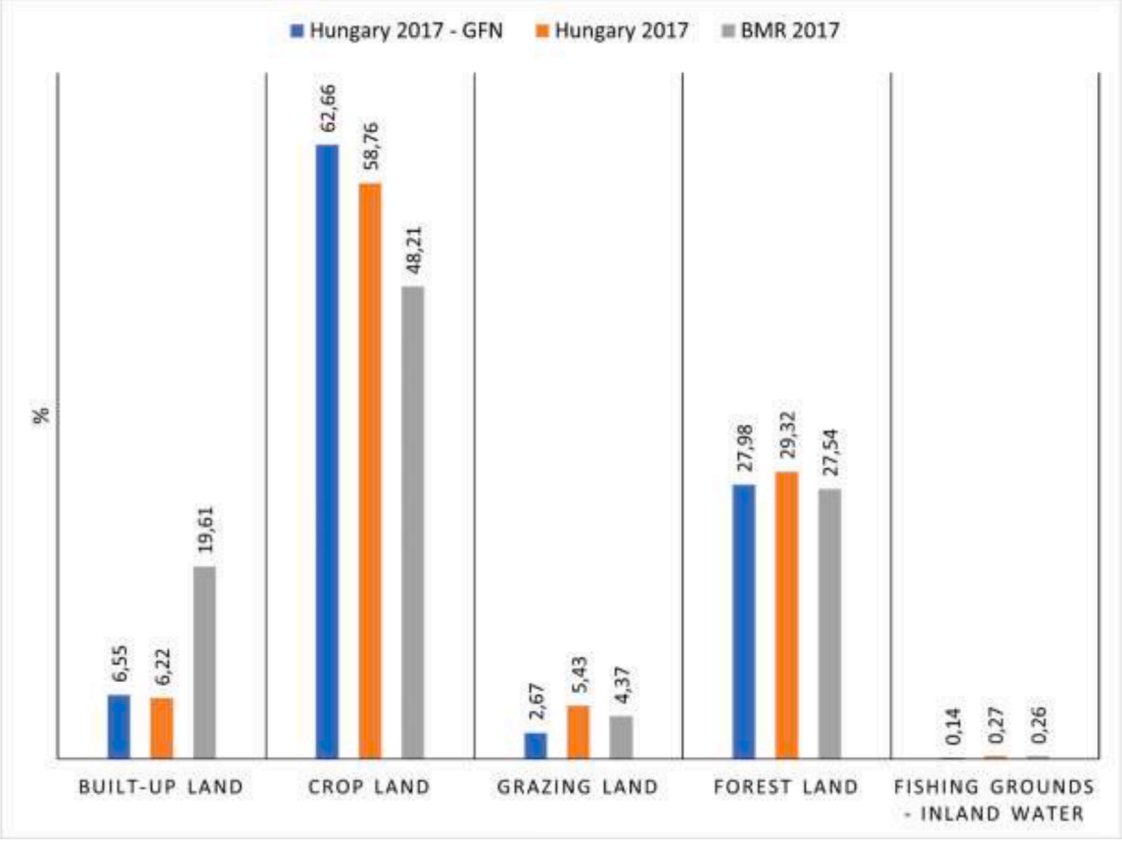
As a result of the changing values of total biocapacity and diverging population trends in the studied geographical units, the difference of the per capita biocapacity in the BMR and Hungary grew from approx. 1.4 to 1.95 gha between 2000 and 2017 (Fig. 1B).

There are also significant differences in the composition of biocapacity between the two areas (Fig. 2). While agriculture accounts for about 60% of the national biocapacity (according to both GFN and our calculations), its share in the BMR is below 50%. The difference is caused mainly by the high share of built-up areas within biocapacity (6.2% vs 19.61%), representing a theoretical biocapacity reserve rather than a resource available in practice (e.g., for food production).

To compare our results with other metropolitan regions of similar size in Central Europe we calculated the changes of biocapacity in total and per capita terms in the urban regions of Prague and Vienna (Table 5). Data for calculation were obtained from Corine Land Cover data-set (CLC) for 2001 and 2016 (EU, 2021). Both metropolitan regions have been affected by steady population growth and the decentralization of people (i.e. suburbanization) since the turn of the millennium (Hatz, 2009; Ouředníček, 2007; Stanilov & Sýkora, 2012; Zévl & Ouředníček, 2021). According to our calculations the total biocapacity value of the metropolitan region stagnated in Prague and decreased in Vienna. However, per capita values of BC decreased in both cases due to

Table 5
Population change and biocapacity (BC) results – in total and per capita terms – for Prague and Vienna (2001, 2016).

Variable	Territorial unit	Prague		Vienna	
		2001	2016	2001	2016
Population (1000 people)	City	1,171	1,276	1,553	1,856
	Agglomeration	792	911	910	993
	Metropolitan Region	1,963	2,187	2,463	2,849
BC total (1000 gha)	City	155	162	136	116
	Agglomeration	1,786	1,831	2,839	2,473
	Metropolitan Region	1,941	1,993	2,975	2,589
BC per capita (gha)	City	0.13	0.13	0.09	0.06
	Agglomeration	2.25	2.01	3.12	2.49
	Metropolitan Region	0.99	0.91	1,21	0.91



Sources:

*GFN

**own calculation

Fig. 2. The internal structure of biocapacity in Hungary and the BMR (2017). Sources: *GFN **own calculation.

population growth, which was especially robust in both cities in the agglomeration zone. Thus, the processes described for Budapest are consistent in the metropolitan regions of Prague and Vienna.

5. Conclusions

Urbanization is among the major challenges of global sustainability with several direct and indirect impacts that are interlinked (Baabou et al., 2017). Urbanization's most obvious direct impact derives from land use changes resuting the loss of bio-productive land and shrinking biocapacity, whereas, its indirect effects are related to growing resource consumption, caused by increasing affluence, and a growth in ecological footprint. Growing spatial concentrations of population and consumption within countries are putting more pressure on ecological resources than in the wider hinterland, therefore, the study of cities and urban regions is pivotal in sustainability assessments (Wiedmann & Allen, 2021). In this paper we summarize the sustainability assessment of urbanization in Hungary through the calculation of the long-term changes of ecological footprint (EF) and biocapacity (BC) at the sub-national level. EF and BC are among the most widely used and accepted sustainability accounting methodologies that provide an opportunity for understanding the relationship between regional socioeconomic and demographic factors and ecological outcomes. The principal novelty of the paper is the simultaneous use of EF and BC in the study of the environmental effects of urbanization at the sub-national (city) level for a longer period of time. Another significance of this study is the joint application of bottom-up approach in the EF calculation, and the use of CLC data in the BC calculation, which is very rare in the literature.

Like many other countries, Hungary belongs to the BC debtors of the world with an ecological deficit, where the EF is greater than the BC, resulting in a strong overshoot. However, as our findings show, the ecological deficit of the country has been gradually decreasing since the early 2000s, which is the outcome of two factors: (1) growing BC due to the higher efficiency of agriculture, and (2) shrinkage of the population (including emigration of the more mobile younger generation). Even though the population consumes more due to steady economic growth and higher income levels, and the per capita EF is also slightly growing, the country's total EF values are stagnating due to population shrinkage.

Our research findings show that the ecological deficit of the country can be associated primarily with the increasing weight of the highly urbanized core of the country, the Budapest Metropolitan Region (BMR). Here both the population and the per capita EF are growing, which means that the share of the urban region within the country's total ecological footprint is steadily on the rise (reaching 31.5% in 2018). At the same time the BC and the ecological resources of the BMR are decreasing due to suburbanization and urban encroachment, which makes the urban region of Budapest increasingly unsustainable. As we demonstrated the trends observed in the metropolitan region of Budapest are consistent with other countries and city-regions in Europe and North America, however, similarities and differences need to be tested by further comparative analysis.

The results also revealed, that, an inverted U-shaped relationship between EF and urbanization can not be justified in the study area. Total per capita EF (Table 2) in the metropolitan region is increasing and economic prosperity is not accompanied by lowering pressure on the environment.

The results of this study provide a reference for future policy formulation in countries similar in size to Hungary. Policy makers in ageing and highly centralized countries should launch environmental awareness programmes in primary metropolitan areas to reduce (or slow down) the growth of EF, and to halt the decrease of BC, making urban development environmentally more sustainable. In countries with a more evenly spread level of urbanization localized policies will likely have smaller effects (Baabou et al., 2017).

On the EF side, policies should focus on two levels (in order to address the two largest – carbon and cropland – components):

- *Improving the infrastructure and environmental efficiency, which may include*:
  - the development of urban transport system (mobility with reduced emissions);
  - the investments in energy efficiency and renewable energy production;
  - the modernization of water and waste management;
  - the promotion of green technologies for the local economy;
- *Promoting the adoption of low resource intensive consumption and more sustainable lifestyle of urban population, which may include*:
  - the promotion of the use of public transportation, sharing schemes, and E- or hybrid vehicles;
  - the promotion of energy conscious lifestyles, including the use of efficient household appliances and avoiding the overuse of energy (and other resources, such as water);
  - the partial self-sufficiency of lower carbon energy sources (like solar panels);
  - the promotion of low resource intensive consumption patterns (like visiting local touristic destinations, considering lower dairy and meat intensive diets, and avoiding overconsumption in general).

Regarding BC, local and regional planning authorities should pursue the concept of the 'compact city' to have better control over urban sprawl (e.g. through zoning and adequate property taxation system), minimize the environmental effects of urban expansion, and prevent the loss of biologically active surfaces (including the maintenance and development of green spaces within city boundaries).

Declaration of Competing Interest

None.

Data availability

The data that has been used is confidential.

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