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Assessing the Ecological Footprint and biocapacity of Portuguese cities: Critical results for environmental awareness and local management

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ABSTRACT

The unsustainable use of our planet's resources needs to be tackled from different angles and multiple levels of governance. As the human population urbanizes, having access to reliable, cross-cutting, quantitative city-level sustainability metrics is key to understanding the environmental impacts of urban dwellers and the role cities can play in the 21st century sustainability challenge. Framing the environmental pillar of urban sustainability with an overarching metric like the Ecological Footprint informs stakeholders and citizens about a city's overall pressure on the biosphere. In Portugal, six cities established a pioneering collaborative project to guide their transition to sustainability and support city governance; this paper presents the results of the first phase of the project. We tracked annual demand for natural resources and ecological services by the city residents and compared it against the "carrying capacity" of the cities' ecological assets. We then assessed the ability of this new data to increase local environmental awareness and support local public policies in Portugal and elsewhere. Lessons from this study inform the ongoing debate on the Ecological Footprint's usefulness as sustainability metric for cities, and point to specific policy insights for managing key consumption sectors and reaching key targets such as the UN SDGs.

1. Introduction

The management of sustainable development ultimately deals with the planet's capacity to support human societies (e.g. Galli, Halle, & Grunewald, 2015; Sterner et al., 2019; Costanza and Daly, 1992). Living within the means of the only planet available for humanity is the starting point to creating a future society where all people can thrive (Meadows, Meadows, Randers, & Behrens, 1972; Meyer & Newman, 2018; O'Neill, Fanning, Lamb, & Steinberger, 2018; Wackernagel, Hanscom, & Lin, 2017). However, "One Planet" is not a goal, but the context that shapes our reality (Ward & Dubos, 1972). Considering that humanity is already demanding more than the Earth's ecosystems can renew, exceeding planetary limits and causing biodiversity decline (WWF, 2018; Rockström et al., 2009; Butchart et al., 2010; Tittensor et al., 2014; Steffen et al., 2015, 2018), the following become fundamental questions: *how can policy makers guide our transition to a sustainable future? How do we serve an expanding global population harboring legitimate growth aspirations (as put forth in the Sustainable Development Goals), while phasing out fossil fuels within a few decades (as promised by the Paris Agreement), and protecting the integrity of the planet's ecosystems and biodiversity (as intended through the Aichi Biodiversity Targets)*?

To ensure global prosperity, the current unsustainable state of the human-environment nexus needs to be tackled from different angles and at multiple territorial levels (Amundsen, Hovelsrud, Aall, Karlsson, & Westskog, 2018; Bruckner, Fischer, Tramberend, & Giljum, 2015; Ingeborgrud, 2018; Rees, 1992). Local governments can play a relevant and meaningful role in this transition process towards a more sustainable and climate-aware development, and yet local initiatives face challenges in delivering significant global environmental sustainability impacts given their scale, autonomy and policy discretion (Bulkeley, 2015; da Cruz & Marques, 2014; Moreno Pires, Fidélis, & Ramos, 2014; Ostrom, 2012; Moreno Pires and Fidélis, 2015).

According to Pearson (2013), cities offer both challenges and opportunities for securing future global sustainability. Cities are home to 55% of the world population (UNPD, 2018) and are foreseen to host up to 65% of the expected 9 billion people by 2050 (FAOSTAT, 2017). Cities critically contribute to direct and indirect global impacts related to energy use, changes in land use and climate, and increases in

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resource consumption (Pearson, 2013; Burger, Brown, Day Jr., Flanagan, & Roy, 2019; Burger et al., 2017). But cities also represent a key point for solutions towards a global sustainability transition through innovative and sustainable planning, participatory governance, economies of scale in infrastructure, and smart resource management at local level (Pearson, 2013; Bettencourt, Lobo, Helbing, Kühnert, & West, 2007; Moore, Kissinger, & Rees, 2013; Lehtonen et al., 2016; Moavenzadeh et al., 2002).

Cities are appropriating the "carrying capacity" of ecosystems outside their borders via trading of food and fibre resources, fuels and energy sources, and goods and services (Burger et al., 2012; Imhoff et al., 2004). According to Rees (1992), the land functionally "occupied" by city residents' demand lies far beyond the city borders thus turning cities into telecoupling nodes (Bruckner et al., 2015), and effectively making their ability to operate a local, regional, and global issue (Burger et al., 2019; Kissinger, Rees, & Timmer, 2011; Yetano Roche et al., 2014). The nested scale of this issue means that actions and policies only at the local level are insufficient.

Framing the environmental pillar of urban sustainability with an overarching metric such as the Ecological Footprint enables the possibility to inform citizens about cities' overall human demand on the planet ecosystems, thus connecting local actions and policies to global sustainability objectives and agendas (e.g. Pearson, 2013; Collins & Flynn, 2015). It also allows indirect tracking of cities' carrying capacity and its appropriation by humans. Building on Rees (1992), the concept of carrying capacity, when applied to humans, can be inverted and interpreted as the maximum rate of resource consumption and waste emission that can be sustained by the ecosystems of a given region.

The human appropriation of ecosystem-level carrying capacity can thus be accounted for via the Ecological Footprint, a resource accounting tool that assesses two specific sustainability criteria: 1) the rate of humanity's renewable resource use compared to the Earth's capacity to renew such resources and 2) the rate of human waste production compared to the Earth's capacity to assimilate waste[1] (Daly, 1990). These criteria are assessed using two distinct metrics: Ecological Footprint and biocapacity (Borucke et al., 2013; Lin et al., 2018). On one side, the Ecological Footprint is a quantitative framework for measuring renewable natural resources and ecological services demanded by a population's consumption activities (at national, regional, city or individual scales); on the other, biocapacity measures the amount of resources and services ecosystems are capable of providing each year (Borucke et al., 2013; Mancini et al., 2018). Comparing Ecological Footprint with biocapacity values allows both of Daly's biophysical sustainability principles to be quantified (Galli et al., 2016). Employing a multiregional input-output analysis then allows Footprint results to be broken down into component parts (see Pearson, 2013; Isman et al., 2018; Weinzettel, Steen-Olsen, Hertwich, Borucke, & Galli, 2014), providing a unique framework to compare different productive sectors or consumption activities within a city's economy, and the varying degrees of pressure these exert on the environment.

In Portugal, a three year project (2018–2020) was developed in collaboration with universities, NGOs, and local government authorities to calculate the Ecological Footprint and biocapacity of six Portuguese municipalities, and to understand the importance of the access to, and interpretation of, Footprint results for local public policies within Portugal. This project aims to build local knowledge and institutional capacity to face complex environmental challenges. Ultimately, it aims to drive new policy programs for the sustainable development of each municipality and influence territorial cohesion policies across the country. The project was implemented in six Portuguese cities (Almada, Bragança, Castelo Branco, Guimarães, Lagoa and Vila Nova de Gaia) using the Ecological Footprint framework, thus allowing results to be compared with those of other regions in the world.

This paper presents the Ecological Footprint and biocapacity results for six municipalities, and discusses implications for environmental awareness and city governance in Portugal. It then suggests specific policy insights for managing key consumption sectors in the local communities of study and to target key UN Sustainable Development Goals (SDGs).

2. Ecological Footprint applications in Portugal: brief review

Sustainability is a trans-disciplinary issue with no single metric able to address its full complexity alone (Galli et al., 2012; Sala, Ciuffo, & Nijkamp, 2015). To deal with this challenge, decision makers must navigate through a wealth of diverse information, data and indicators (Pulselli, Moreno Pires, & Galli, 2016), whose interpretation might be difficult. Quantitatively assessing and monitoring each dimension of sustainability (e.g., the environmental pillar) is a challenge that municipalities face, in Portugal and elsewhere. Even more problematic is to identify and use standardized sustainability assessments tools allowing comparison between cities and other territorial levels (Moreno Pires et al., 2014). Ecological Footprint and biocapacity accounting represents a standardized methodology that can be applied across varying spatial scales, although very few studies have conducted assessments of these two metrics at the municipal scale of analysis (e.g., Bagliani, Galli, Niccolucci, & Marchettini, 2008).

In the case of Portugal, there is limited research concerning the application of the Ecological Footprint methodology. Ecological Footprint applications exist to the industry sector (Costa et al., 2018) but, as far as we know, this is the first peer-reviewed study dealing with Ecological Footprint and biocapacity accounting for Portuguese municipalities. Nonetheless, a search in the grey literature revealed two interesting examples of Ecological Footprint applications in Portuguese cities. First, the city of Cascais, located in the Metropolitan Area of Lisbon, analyzed the Ecological Footprint and biocapacity of the municipality via a top-down approach using Global Footprint Network, 2006 Footprint Standards GFN, 2009 and 2005 data (Daniel, 2012; Sousa, 2009). This study concluded that the Ecological Footprint of the city was 18% higher than the national average (5.2 gha per capita in Cascais compared to 4.4.gha per capita in Portugal) and that the main Ecological Footprint components were "food and non-alcoholic beverages" (making up 32% of the overall municipal Ecological Footprint) and "housing, water, electricity, gas and other fuels" (making up 14%) (Daniel, 2012). The second study was conducted in the city of Almada, also located in the Metropolitan Area of Lisbon, which is one the municipalities that joined the project presented in this paper. In 2011, Almada was the first city in Portugal to incorporate Ecological Footprint results into its territorial planning process and discuss their implications for land-use and environmental policies (CMA, 2011).

Similarly, scientific literature concerning the application of other Footprint indicators such as Carbon and Water Footprints to Portuguese cities is limited. A review on cities and greenhouse gases emissions by Hoornweg, Sugar, and Gómez (2011) reported the carbon footprints of 100 cities, including the city of Porto in Portugal. Another study by Ivanova et al. (2017) mapped the carbon footprints of EU regions, including Portuguese regions. Burman et al. (2018) performed a review of life-cycle assessments, Water Footprints, and Carbon Footprints in Portugal, and found seven Water Footprint studies and six Carbon Footprint studies; however, all papers concerned industry applications. Moran et al. (2018) presents the Carbon Footprint of 13,000 cities around the world, including two Portuguese cities, Porto and Lisbon.

The few studies identified only analyzed big cities in metropolitan regions. It was not possible, to the best of our knowledge, to map a comparative assessment of different cities with different population sizes and geographical locations outside metropolitan areas. This paper aims to contribute to the gap in city Footprinting theory and practice in Portugal.

[1] It should be noted that current Ecological Footprint methodology tracks a specific type of waste only: carbon dioxide emissions (Borucke et al., 2013).

3. Materials and methods

3.1. Overview of Ecological Footprint and biocapacity accounting

At the country level, the Ecological Footprint measures the global ecological assets (i.e., the biologically productive land and sea areas) required by the population of a given country to produce the natural resources and services that are harvested or used within its geographical boundaries, plus those used abroad and imported through trade, minus those exported for consumption elsewhere. This can be expressed with the equation below:

$$EF_C = \sum_{i=1}^{n} \frac{P_i}{Y_{W,i}} * EQF_i + \sum_{i=1}^{n} \frac{I_i}{Y_{W,i}} * EQF_i - \sum_{i=1}^{n} \frac{E_i}{Y_{W,i}} * EQF_i$$

where,

- P_i, I_i and E_i are the produced, imported, and exported amount of each product *i* (in tonnes per year), respectively;
- $Y_{W,i}$ is the world-average (w) annual yield (in t $w$ha^{-1} yr^{-1}) for the production of each product *i*, given by the tonnes of product, *i*, produced annually across the world divided by all areas in the world on which this product is grown; and
- EQF_i is the equivalence factor for the land type producing each product *i*. It captures the difference between the productivity of a given land type and the world-average productivity of all biologically productive land types (Borucke et al., 2013; Galli, 2015; Lin et al., 2018).

The resource and services considered include plant-based food and fibre products, livestock and fish products, timber and other forest products, waste absorption (CO_2 from burning fossil fuels), and space for urban infrastructure (Borucke et al., 2013). The size of the ecological assets appropriated by a country's population through its consumption activities is derived by dividing the amount of resource and services it uses by the yield of the land type producing such resources and services. The values obtained are then multiplied by equivalence factors and summed together to generate final Ecological Footprint values.

Meanwhile, the biocapacity (BC) of a country measures the ecological assets available within the national borders (including forest lands, grazing lands, cropland, fishing grounds and built-up land) and their capacity to produce renewable resources and ecological services (Mancini et al., 2018) as indicated in the equation below (see Borucke et al., 2013 and Lin et al., 2018 for further methodological details):

$$\text{BC} = \sum_{i} A_{N,i} \cdot YF_{N,i} \cdot EQF_i$$

where,

- $A_{N,i}$ is the ecological asset (i.e., the biologically productive land and sea area) that is available for the production of each product *i* in the nation;
- $YF_{N,i}$ is the nation-specific yield factor for the asset producing products *i*; YFs are country- and asset-specific and thus capture countries' differing levels of productivity for particular land use types; and
- EQF_i is the equivalence factor for the asset producing each product *i*.

National Footprint and biocapacity Accounts (NFAs) provide Ecological Footprint and biocapacity values for nearly 200 countries, regions, and the world, and are produced annually by the NGO Global Footprint Network.[2] Results for these two metrics are expressed in global hectares (gha), a unit representing area of world-average productivity (Galli, 2015; Galli et al., 2017; Kitzes, Galli, Wackernagel, Goldfinger, & Bastianoni, 2007), so that they can be compared to derive "ecological balances" between the supply and demand of natural resources (Galli, Wackernagel, Iha, & Lazarus, 2014).

When a country's consumption of natural resources and services is greater than the capacity of its ecosystems to supply them (Ecological Footprint > biocapacity), the country is said to be in "biocapacity deficit". This can occur three ways: 1) a country imports the natural renewable resources it consumes but does not produce; 2) a country overharvests its own resources through unsustainable agricultural practices, overgrazing, overfishing, or deforestation, and 3) a country uses global commons for instance by emitting more CO_2 in the atmosphere than it has the capacity to sequester (Niccolucci et al., 2011). As such, by importing biocapacity from other nations and exploiting the global commons, nations can consume more than their local ecosystems can renew, at the expense of the external ecosystem's carrying capacity, and without necessarily degrading or depleting their local biocapacity. Conversely, when a country's availability of natural resources and services is greater than the residents' demand (biocapacity > Ecological Footprint), the country is said to run a "biocapacity reserve". Ecological balance analyses become increasingly more critical at lower scales of analysis such as that of cities, where the reliance on natural resources and services outside of municipal borders is greater.

3.2. Ecological Footprint calculation of Portuguese municipalities

The feasibility and accuracy of sub-national calculations (i.e., for cities, provinces or regions) are generally limited by the availability of data. This means Ecological Footprint practitioners at this scale of analysis must opt for either a bottom-up approach which requires extensive data collection (e.g. Moore et al., 2013) or a top-down approach based on national Footprint data supplemented with local data (e.g. Pearson, 2013). An extensive review of various studies adopting the two different approaches as well as a discussion of the strengths and weaknesses of these approaches is discussed by Pearson, 2013. This study employs the top-down methodology which allows for consistent comparisons between city and national Footprint and biocapacity results, and avoids time and cost constraints of extensive local data collection and/or life cycle assessments (Fig. 1).

Using 2014 Ecological Footprint results for Portugal (Global Footprint Network, 2018), a national Consumption Land Use Matrix (CLUM) was calculated by applying Ecological Footprint results to the economic Multi-Regional Input-Output (MRIO) GTAP 9.0 model (Pearson, 2013; Isman et al., 2018; Narayanan and McDougall, 2015) (Fig. 1). This step allowed national land-based Ecological Footprint results to be translated into activity-based Ecological Footprint results for Portugal, which sheds lights on the extent to which specific human activities exert pressure on specific ecological assets, measured in global hectares per person (Galli et al., 2017). Portuguese CLUM results provide per-capita national average Ecological Footprint values for each consumption category (Table 1), and serve as the starting point for sub-national analyses. These latter are based on the Nomenclature of Territorial Units for Statistics (NUTS), a common classification established by the European Union for statistical purposes at different territorial scale (EU, 2015).

Supplemental local and international data was used to estimate household expenditures for the six municipalities from 2011 to 2016, which were then used to derive Footprint scaling factors for the appropriate consumption sub-category. We used municipal-level data on purchasing power obtained from the Portuguese National Statistical Institute to calculate city-specific scaling factors for each year of study[3]

[2] The latest edition of the annual National Footprint and biocapacity Accounts was issued in early 2019 with data points up to 2016. Results are available on the open data platform at https://data.footprintnetwork.org.

[3] More precisely, the cited statistical sourced provides data for the years 2011, 2013 and 2015; data for the year 2012, 2014 and 2016 were extrapolated from the available data years.

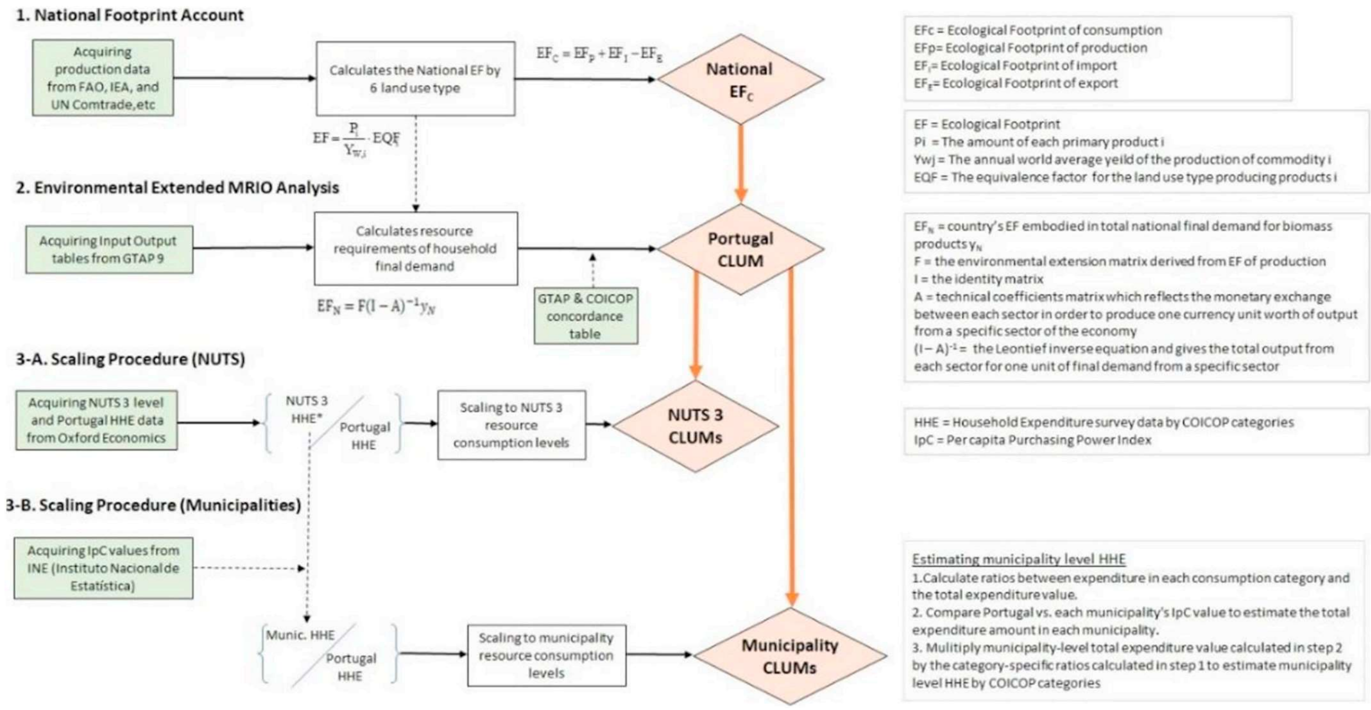

Fig. 1. Flowchart of the methodology used to calculate the Ecological Footprint of the six Portuguese municipalities.

Table 1
Consumption Land-Use Matrix (CLUM) of Portugal for data year 2014, with results reported in global hectares per person (Global Footprint Network, 2018).

[gha person^{-1}]	Cropland	Grazing Land	Forest Land	Fishing Grounds	Built-up Land	Carbon	TOTAL
Household consumption	**0.76**	**0.25**	**0.09**	**0.31**	**0.02**	**1.56**	**2.99**
1. Food and non-alcoholic beverages	0.49	0.16	0.01	0.26	0.00	0.16	1.08
2. Alcoholic beverages, tobacco and narcotics	0.07	0.01	0.00	0.01	0.00	0.06	0.16
3. Clothing and footwear	0.05	0.04	0.01	0.01	0.00	0.12	0.22
4. Housing, water, electricity, gas and other fuels	0.02	0.00	0.02	0.01	0.00	0.30	0.36
5. Household furnishings, equipment and maintainance	0.03	0.01	0.00	0.01	0.00	0.07	0.12
6. Health	0.01	0.00	0.00	0.00	0.00	0.04	0.06
7. Transportation	0.05	0.01	0.02	0.02	0.00	0.64	0.75
8. Communication	0.00	0.00	0.00	0.00	0.00	0.01	0.02
9. Recreation and culture	0.01	0.00	0.02	0.00	0.00	0.07	0.11
10. Education	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11. Restaurants and hotels	0.00	0.00	0.00	0.00	0.00	0.01	0.01
12. Miscellaneous goods and services	0.01	0.01	0.00	0.00	0.00	0.07	0.10
Government	**0.05**	**0.01**	**0.01**	**0.01**	**0.00**	**0.18**	**0.26**
Gross Fixed Capital Formation	**0.03**	**0.02**	**0.04**	**0.01**	**0.01**	**0.34**	**0.44**
Total	**0.84**	**0.27**	**0.14**	**0.33**	**0.02**	**2.09**	**3.69**

(INE, 2017). This data, called the *Indicador* per Capita *do Poder de Compra Concelhio* (IpC) in Portuguese (or relative purchasing power), measures the per capita purchasing power of each Portuguese municipality relative to a national benchmark of 100. Scaling factors were calculated as the ratio of municipal to national IpC, and applied to each consumption category.

To estimate total household expenditure at the municipality level from 2011 to 2016, the scaling factors for each year of study were applied to the total national household expenditure at purchasing power parity (PPP) over the same time period (Oxford Economics, 2014). Household expenditure data of detailed sub-categories was then calculated for each municipality based on the relative contribution of each sub-category to the total expenditure at the related NUTS 3 level from 2011 to 2016 (NUTS classification and related household expenditure results for the six municipalities are reported in Tables S1 and S2 of the Supplementary material). Level 3 of the NUTS classification indicates small regions for specific diagnosis and is the highest resolution level for which household expenditure data is available in subcategories of consumption (based on the COICOP classification[4]). Ecological Footprint results for the six municipality-related NUTS 3 territories are shown in the Supplementary material (Table S3).

Finally, city-specific Footprint scaling factors for each year and each detailed consumption category were calculated using the ratio between city and national expenditure. These values were then used to calculate

[4] The Classification Of Individual Consumption According to Purpose (COICOP) is the internationally agreed classification system for reporting household consumption expenditures. It is published by the UN Statistics Division for use in expenditures classification, National Accounts, Household Budget Survey and the Consumer Price Index. Available at: https://unstats.un.org/unsd/iiss/Classification-of-Individual-Consumption-According-to-Purpose-COICOP.ashx.

the final Ecological Footprint of each detailed household consumption category at the city level from 2011 to 2016. For the Ecological Footprint associated with Government and Gross Fixed Capital Formation (GFCF) for each city, the same value as the NUTS 3 region was set, assuming that the entire population within a certain region carries an equal share of the government and GFCF consumption of that region. Government and GFCF Footprint values for NUTS 3 regions, in turn, were calculated by scaling Portugal's government and GFCF values by the ratios of the household Footprints of consumption by land type of the nation and each region. The final Ecological Footprint of consumption value for each municipality was then obtained by summing up the Footprint of each consumed category.

3.3. Biocapacity assessment for Portuguese municipalities

Biocapacity values for the six municipalities were calculated using the standard methodology reported in Section 3.1 (see Eq. (2)). The spatial extent of each land type was calculated using the 2012 CORINE land-cover dataset (CLC, 2012) (Fig. 2). Due to the lack of land cover data in 2014, the 2012 CORINE dataset was used to scale Portugal land area values from the NFA 2018 edition to each district[5] and municipality. Various CORINE land cover types were aggregated to correspond with the NFA biocapacity land types, based on a classification system reported in Table S4 (see Supplementary material).

Next, Yield Factors (YFs) were calculated for each municipality using ArcGIS (version 8.3), by conducting a spatially explicit assessment of biological productivity, measured using average net primary productivity (NPP),[6] for cropland, grazing land, and forest land types. Annual NPP data was obtained from the Terra MODIS (Moderate Resolution Imaging Spectroradiometer) dataset, at a spatial resolution of 500 m Running et al., 2015. The raster NPP data of each year was overlaid with CORINE land cover data (2012) to calculate the average NPP of each land type (see Supplementary material, Table S5). Sub-national YFs were then calculated using the following the equation:

$$YF_{sub-national} = \frac{Mean\ NPP_{region}}{Mean\ NPP_{Portugal}} \times YF_{Portugal}$$

YFs for the remaining biocapacity categories (built-up land, inland water, and marine areas) were assigned following the standard methodology: built-up land YF was set equal to cropland, because we assumed that urban areas were built on productive agricultural lands (Borucke et al., 2013). Inland water was given a YF of 1 due to the lack of a global dataset on freshwater ecosystem productivity (Borucke et al., 2013). And marine areas were assigned Portugal's YF value, 0.79. Portugal's YF was calculated using the standard methodology described in Borucke et al. (2013).

Finally, we used national EQF values from the NFAs 2018 edition (Global Footprint Network, 2018) to ensure consistency and comparability with National Footprint and biocapacity results, although the availability of additional local data would have allowed us to further adjust the EQFs to local conditions.

4. Results and discussions

The six municipalities in this study vary in population size as well as in socio-economic (Table 2) and geographical (Fig. 2) contexts: two are located in large metropolitan areas (Almada and Vila Nova de Gaia), two are in the interior far from the coastline (Bragança and Castelo Branco), one is on the southern coast of the country (Lagoa), and the last lies to the north near major cities (Guimarães). The demographic and geographical diversity of these cities makes for an engaging assessment of the differences and similarities of the obtained Footprint results.

In this section, the following key questions are discussed: What are the Ecological Footprints of the six cities from 2011 to 2016 and how do these results compare to the national average? Which ecosystems do municipalities place the most pressure on and to what extent do city residents depend on resources and services from outside municipality borders? What are the main drivers of the municipal Ecological Footprints? How much biocapacity is available within municipality borders and how does a city's biocapacity contribute to the overall biocapacity of the country?

4.1. Ecological Footprint accounting for the 6 cities and Portugal: overview

Compared with the average Ecological Footprint of Portugal, three cities have higher per capita Footprints (Almada, Bragança and Castelo Branco), one has a similar per capita Footprint (Vila Nova de Gaia), and two have lower per capita Footprint than the national average (Guimarães and Lagoa). The contribution of each municipality to the total Ecological Footprint of Portugal in 2016 shows the influence of the population dimension of each city: Vila Nova de Gaia contributed 2.9%, Almada 1.7%, Guimarães 1.4%, Castelo Branco 0.5%, Bragança 0.3%, and Lagoa 0.2% (Table 3).

Meanwhile, the Ecological Footprints of all cities are higher than the world-average biocapacity available for each person (1.7 gha in 2016) indicating that, if the entire world population lived like the citizens of these countries, humanity would require between 1.9 and 2.4 planets (Table S4). Despite the fact these municipalities have been strongly active in local policies to tackle environmental issues in Portugal, results show that these policies are insufficient to address municipal and global overshoot of natural resource consumption.

4.2. Per capita Ecological Footprint vs. biocapacity for the 6 cities and Portugal: pressures

In 2016, the Ecological Footprint of the residents of each of the six municipalities was higher than the respective municipal biocapacities (and higher than the national per capita biocapacity) (Table 3), indicating a biocapacity deficit situation for all six cities. This means that more resources are consumed than are available within the boundaries of each municipality. This imbalance is most apparent in four cities (Almada, Guimarães, Lagoa and Vila Nova de Gaia), mainly due to the limited natural resource endowment of those territories (Fig. 3).

For all municipalities, the greatest pressure is placed on the carbon sequestration capacity of world forests, as indicated by the carbon Footprint component making up more than half of the total Footprint value. This result highlights the impact that CO_2 emissions have on the Ecological Footprint (see also Mancini et al., 2016). Even a small reduction of CO_2 emissions would result in a significant Footprint reduction thus underlining the paramount importance of decarbonizing the economy. The Portuguese government plans to achieve this target by 2050 by transforming the energy, transportation, waste, and agricultural sectors, as well as forestry and land use (Barata, Pinto, Sousa, Aguiar-Conraria, & Alexandre, 2018). Public policies that promote the widespread use of renewable energy and energy efficiency in all sectors and ban fossil fuels will produce a positive impact and are thus highly needed.

After carbon, the highest pressures from municipal Ecological Footprints is placed on cropland (with an average 23% of the total value), fishing grounds (9%), grazing land (7%), forest land (4%) and built-up land (1%).

[5] Districts are the first-level administrative subdivision of mainland Portugal, serving as the area of jurisdiction of a civil governor. Data from the Corine Land Cover database is provided by districts, which is thus used as the larger scale boundaries for the biocapacity analysis of municipalities under study.

[6] NPP is the net amount of energy a plant accumulates during a certain period of time. It is calculated by subtracting plant respiration (the total amount of energy/mass lost by the plant as it breathes) from gross primary productivity (the total amount of energy/mass taken in by the plant) (Foley et al., 1996).

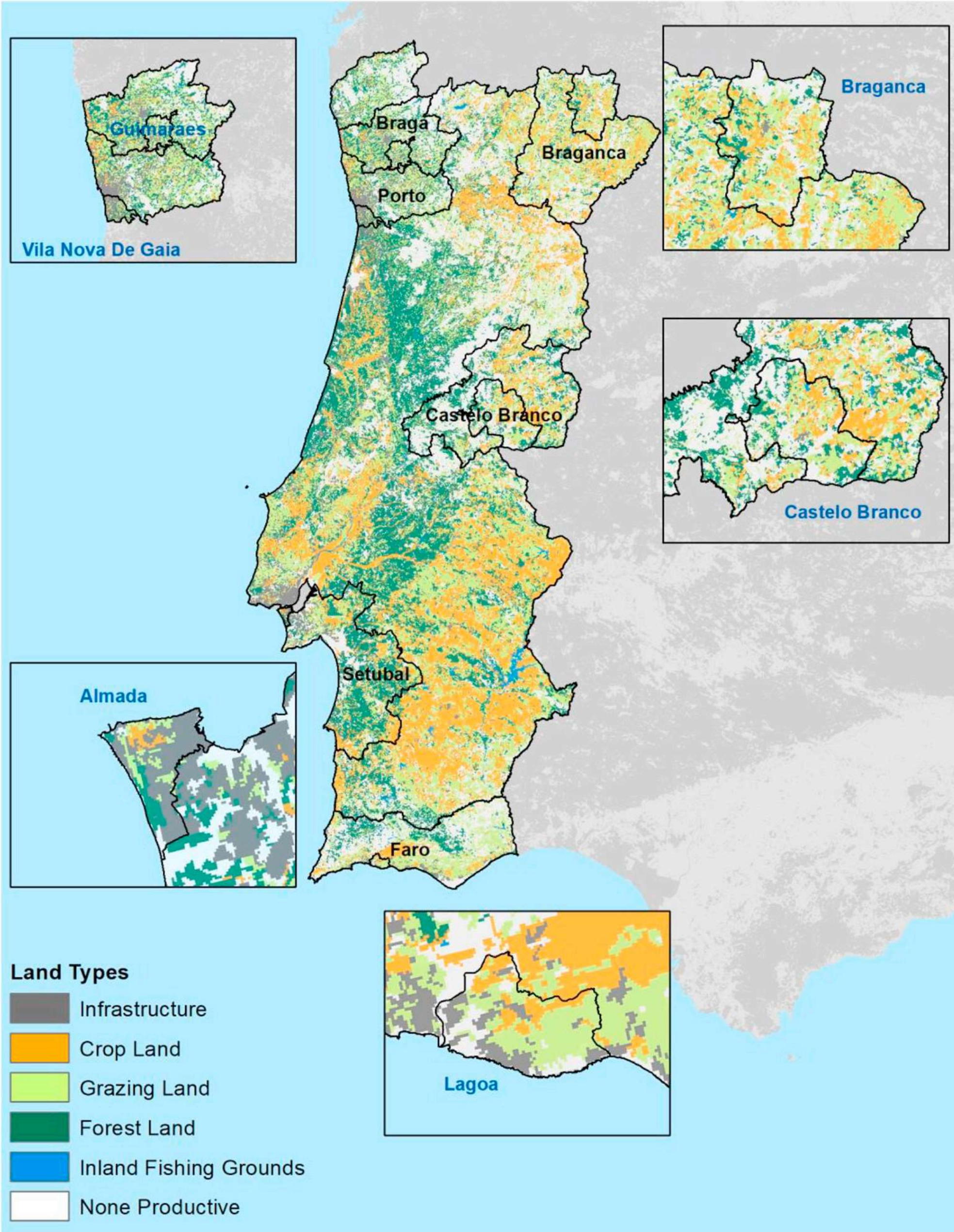

Fig. 2. The distribution and extent of biocapacity land types for Portugal, the six districts referred to as the larger scale boundaries of the six municipalities under study (black font names in the figure), and the six municipalities involved in this project (blue font names in the zoom-in rectangles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

All municipalities experienced similar Ecological Footprint trends from 2011 to 2016, reaching the highest per capita value in 2011 (except Guimarães) and the lowest in 2013 or 2014 (see Fig. 4). This is likely the result of a contraction in consumption following the economic downturn that Portugal and other Mediterranean countries faced since 2008. Since then, the Ecological Footprint has been steadily increasing, following an economic recovery (see also Galli et al., 2015) that has been particularly remarkable in Portugal. There, a reduction of austerity measures, the promotion of consumption-stimulating instruments (e.g. pay rises in the public sector, state pension increases, reduction in taxes as well as in energy and public transport costs), reduced unemployment rates, increased international exports and a record growth in the tourism sector seems to have increased consumption again after the post 2008 contraction.

The fact that Almada was found to be the city with the highest per capita Footprint in 2016 is likely due to its proximity to Lisbon, the capital city and region in Portugal with highest incomes, and thus affecting the spending power of residents – Almada is the studied city with the highest purchasing power per Euro (IpC), and which has remarkably benefited from the country's flourishing tourism.

4.3. Per capita Ecological Footprint vs. biocapacity for the 6 cities and Portugal: drivers

Activity-based Ecological Footprint results derived from municipal Consumption Land-Use Matrices revealed that the two main drivers were food consumption and transportation (Fig. 5). Food consumption is the most critical challenge to address as it constitutes the main Footprint driver across all municipalities and all investigated years. Although city-specific features must be taken into account, a few

Table 2
Population and socio-economic context of the six Portuguese municipalities in 2016.

Municipalities	Population[a]	Population Density[b]	Ageing Index[c]	Resident population aged 15–64[d]	Population with higher education (%)[e]	Purchasing power per capita (IPc)[f]
Almada	169,510	2417.2	148.5	62.6	17.0	109.7
Bragança	33,900	28.9	206.3	64.6	18.0	98.0
Castelo Branco	53,317	37.1	199.1	62.9	14.9	97.4
Guimarães	154,458	641.0	118.4	70.5	9.3	90.6
Lagoa	22,793	258.3	136.3	65.0	10.0	81.4
Vila Nova de Gaia	300,587	1784.3	126.6	68.0	14.8	99.6
Portugal	10,325,452	112.0	148.7	65.0	13.8	100.0

[a] Resident population, annual average (2016). Source: PORDATA, 2019.
[b] Average no. of individuals per Km^2 (2016). Source: PORDATA, 2019.
[c] The ratio of the number of elderly persons of an age when they are generally economically inactive (aged 65 and over) to the number of young persons (from 0 to 14) (2016). Source: PORDATA, 2019.
[d] Resident population aged 15–64 (2016). Source: PORDATA, 2019.
[e] Resident population aged 15 and over by the highest educational qualifications obtained, according to the 2011 Census (%). Source: PORDATA, 2019.
[f] Purchasing power per capita (2015). Source: PORDATA, 2019.

Table 3
Ecological Footprint (EF) and biocapacity (BC) results – in total and per capita terms – for the six Portuguese municipalities in 2016.

Cities	EF total (1000 gha)	BC total (1000 gha)	EF per capita (gha)	BC per capita (gha)	Municipal overshoot day	Planets Earth required
Almada	692	41	4.08	0.24	May 27th	2.4
Bragança	136	91	4.01	2.68	May 30th	2.4
Castelo Branco	214	123	4.02	2.31	May 30th	2.4
Guimarães	566	29	3.66	0.19	June 13th	2.3
Lagoa	74	20	3.25	0.89	July 4th	2.2
Vila Nova de Gaia	1178	51	3.92	0.17	June 3rd	1.9
Portugal	38,079	13,214	3.94	1.28	June 2nd	2.3

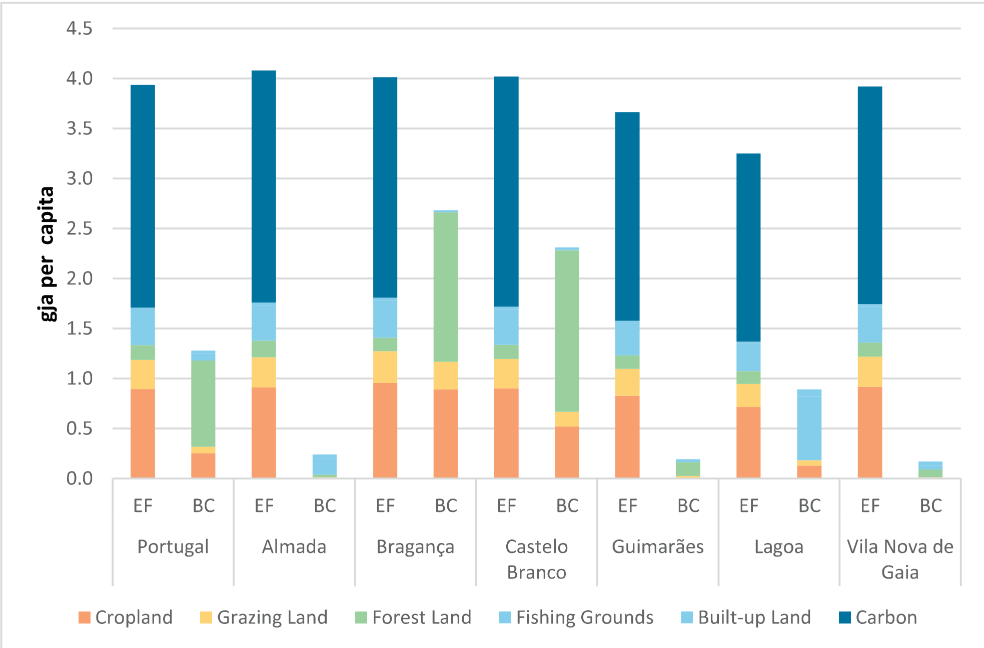

Fig. 3. Per capita Ecological Footprint and biocapacity of Portugal and the six municipalities in 2016, broken down by land component.

common paths exist for municipalities to reduce their food Footprint while achieving SDG targets, such as: changing dietary preferences, providing options for higher quality and locally produced food, tackling food waste through local policies (SDG 12.3), implementing green public procurement for food (SDG 12.7), and providing incentives for sustainable food production systems at the local level (SDG 2.4). The role of national governance is then critical to connect local and national policies and strategies for healthy and sustainable food systems.

The contribution of transportation on the Ecological Footprint is also very significant. The Footprint of transportation is influenced by mobility options, public services, infrastructure, and ultimately citizens' preferences and behaviors. Local public transportation policies should be directed towards improving the quality and efficiency of existing public transportation services; expanding and creating new transportation systems; and diversifying mobility options, such as bicycle infrastructure, integrated transport options and car-sharing practices. Also, local governments can restrict the use of motor vehicles, for example, in city centres thus reducing air pollution and favouring an

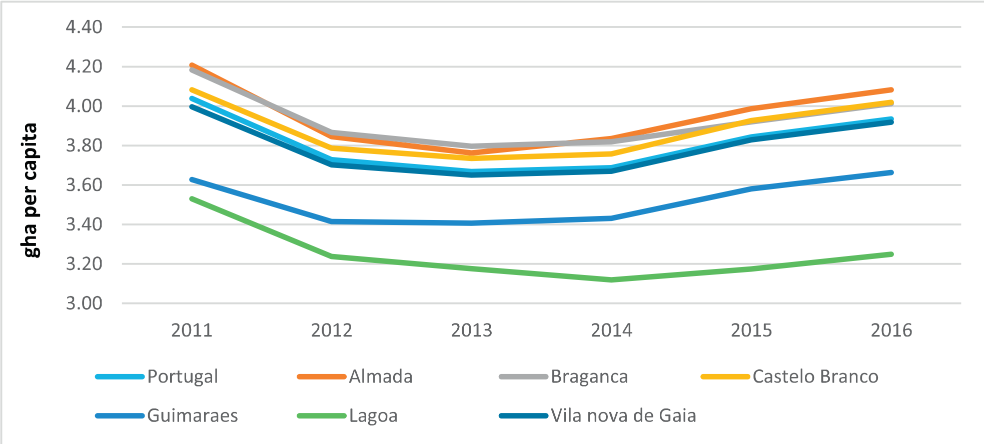

Fig. 4. Per capita Ecological Footprint of Portugal and the six municipalities, from 2011 to 2016.

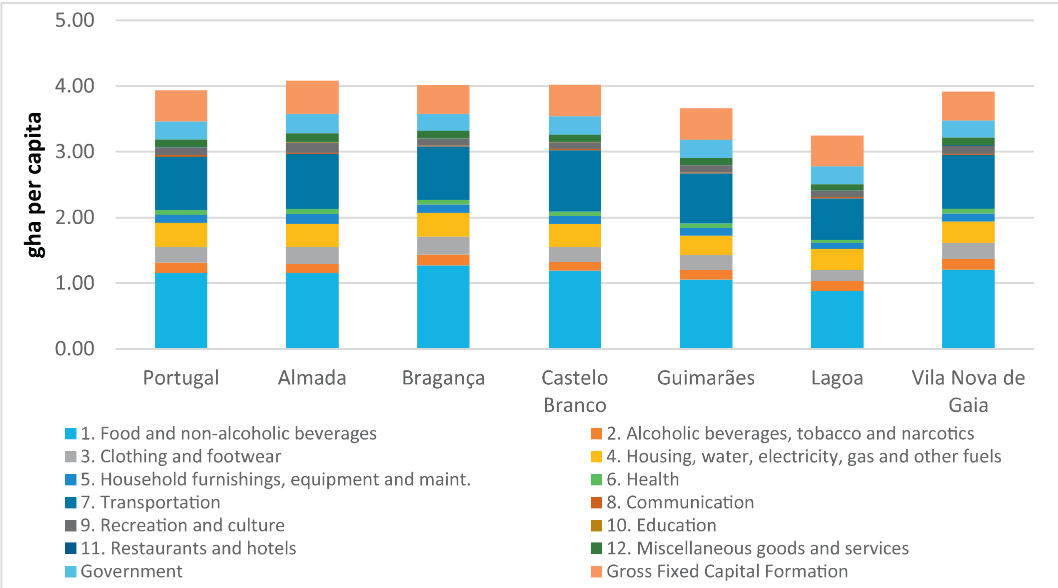

Fig. 5. Per capita Ecological Footprint of Portugal and the six municipalities by consumption categories, in 2016.

active lifestyle. Moreover, because mobility options depend greatly on individual choice, transportation policies should not neglect the importance of education to change habits. These actions contribute to progress towards SDG 11.2. Awareness campaigns for the reduction of climate change impacts and early warning must also be considered, stressing SDG 13.3. However, we acknowledge that transport policies at the local level are very dependent on national policy options but unfortunately, for decades the central government of Portugal has created incentives for using private cars through investments in roads and car infrastructure, while disinvesting in the railway system. Creating conditions to revert this trend at the local and national level is essential to reduce the Ecological Footprint of these (and other) Portuguese municipalities, as well as the country as a whole.

All other household categories contribute less to the total Ecological Footprint of the municipalities but should not be neglected. For instance the relatively low housing Ecological Footprint of cities may partially be explained by the national context, since there is no data for the energy mix at the local level. In 2016, the CO_2 intensity of the energy mix of Portugal was 2.14 t CO_2/toe, thus higher than the EU-28 (2.00 t CO_2/toe) (IEA, 2018). However, in the same year, 28.4% of the gross final energy consumption in Portugal originated from renewable energy sources, while in EU-28 this percentage was significantly lower (17.0%) (EUROSTAT, 2018). Nevertheless, a recent study has assessed the energy poverty vulnerability index of Portuguese municipalities – and respective civil parishes – and concluded that there are many hotspots for local action, regarding both space heating and cooling problems and many opportunities for national and local energy efficiency policies and instruments (Gouveia, Palma, & Simões, 2019). In addition, the household Footprint is likely underestimated. “Housing, water, electricity, gas and other fuels” is the Ecological Footprint associated with the upkeep and maintenance of a dwelling, which includes the indirect Ecological Footprint associated with the purchase of water, electricity, gas and other fuels. But this estimate does not include direct emissions from the actual combustion of fossil fuels for heat or cooking in a dwelling.

4.4. Biocapacity of cities: local endowment and national contribution

Biocapacity results allow local leaders and administrators to understand the natural endowment of their territories, which needs to be safeguarded and maintained to ensure a long-term supply of key, life-supporting resources and ecosystem services (SDG 15). Results from the analysis conducted in this study show very different results, with per capita biocapacity values ranging from 0.17 gha to 2.68 gha.

Fig. 6. Ecological Footprint calculator home page and results page for the municipality of Guimarães, available at https://www.cm-guimaraes.pt/p/calc_pegada_ecologica.

Per capita biocapacity of Bragança is more than double the national average (110% greater) and that of Castelo Branco is 80% greater than the national average as both the territories have greater endowments in grazing land, cropland and forest land (Fig. 3). These results show that both territories are predominantly rural, with significant forested areas and important agricultural and livestock activities, while inland fishing grounds have almost no expression. Vila Nova de Gaia, Guimarães, Almada and Lagoa have biocapacities that are lower than the national average. The contribution of each municipality to the total biocapacity of Portugal is as follows: Castelo Branco, 0.9%; Bragança, 0.7%; Vila Nova de Gaia, 0.4%; Almada, 0.3%; Guimarães, 0.2%; and Lagoa, 0.2% (Table 2).

The availability of bio-productive ecological assets within the municipality borders, measured through biocapacity, is fundamental to accommodate the demand for natural resources measured by the Ecological Footprint, which captures the resources, regardless of their origin, that are consumed by the residents of a municipality. This implies that while resource demand can be extended far away from national borders, resource supply is physically restricted by the limits and characteristics of the territory. Two processes can increase biocapacity: regaining land, for instance, by converting unused areas of the cities into urban parks or gardens; and, to a lesser extent, increasing the yield of existing land by boosting the productivity of green areas. In some cases, it may be hard to significantly increase the total amount of biocapacity. For that reason, it is paramount that policymakers design policies that protect, preserve, restore and reinforce all the natural resources that support biocapacity, particularly in the presence of climate change challenges and stressors such as forest fires. This means that it is vital to protect biodiversity, ecosystems, and the valuable ecological services that they provide at the local level, thus contributing to SDGs 11.4 and 11.7. The development of tools to understand and assess ecosystem services (provisioning, regulation, cultural and supporting services) in the local territories should thus be a priority for policy makers to be able to better recognize their (social, economic and natural) value and protect these "invisible" services. Policy support could be also directed towards innovation (e.g., clean technologies, energy efficiency, ecotourism and circular economy) in key economic sectors to guarantee increased economic benefit and livelihood while preserving the local biocapacity and biodiversity.

Finally, as this is one of the first applications of GIS-based biocapacity assessment at the local level, we suggest that further research needs to be conducted to increase the resolution of the assessment and their representativeness of the local ecological assets.

4.5. Raising public awareness with municipal Ecological Footprint calculators

The transition to a sustainable society can only be achieved through widespread participation and support of citizens. While the first phase (year 2018) of this project was geared towards informing and engaging with local government stakeholders, phase 2 was designed to also generate community involvement. In this second phase, which is now being implemented and will be concluded in December 2019, Ecological Footprint and biocapacity assessment results from phase 1 have been used to build an Ecological Footprint calculator for each municipality.

Generally, online Footprint calculators diverge from the technical Ecological Footprint accounting tool described in this study in that they are user-friendly tools to calculate an individual's impact on the environment, and provide a platform for individuals to participate in the development of sustainable actions and policies that are unique to each community needs. The six calculators developed by this project, which are similar to Global Footprint Network's personal Footprint Calculator (Global Footprint Network, 2019), have been customized with municipalities' Consumption Land-Use Matrix results from this study to reflect the unique consumption patterns of the municipalities. Further details on the calculation mechanism that underpins Global Footprint Network's personal Footprint calculator are provided in Collins, Galli, Patrizi, and Pulselli (2018), alongside with an assessment of the calculator's usefulness as an environmental awareness tool.

The Footprint calculator asks the user a series of lifestyle questions about food, housing, energy, and mobility, and provides users with their personal Ecological Footprint results by both consumption category (food, housing, mobility, goods, and services) and Footprint component (cropland, grazing, fishing grounds, forest products, built-up land, and carbon) in global hectares (Fig. 6), also allowing comparison with the country's average. It also provides info on alternative solutions to lower once Footprint.

This tool enables civil society to understand the multiple, competing human demands on the environment, while gaining awareness about the extent of an individual's pressure on the biosphere. Presented to the six local communities in May 2019, these calculators will be promoted by the local administrations and used to increase the environmental awareness of the residents and stimulate alternative low Footprint behaviors. A controlled study will be conducted with local "Footprint ambassadors" from each municipality during the second half of 2019: civil society members will be trained on the Ecological Footprint and its implications, before their calculator's results will be collected at multiple points in time to monitor the influence of using the calculator over their daily choices. Upon completion of the study, workshops and roundtables with municipal stakeholders, NGOs and the civil society will be conducted to discuss the implications of the Footprint results and understand what changes in daily choices citizens of the six municipalities are willing or unwilling to make. Insight from this controlled study is expected to guide the local administration in the identification and implementation of effective policy options.

5. Conclusions

As the global population increases and ever more migrate to cities, city governance will need to address sustainability from more than a local perspective. Meaningful indicators are needed to quantitatively capture the resource security of cities, a core aspect of a city's (un) sustainability. Such metrics connect the city with the wider global context and identify sectors where effective macro and micro intervention for sustainability can be introduced. Urban planning and development require adequate quantitative tracking of ecosystems' limited capacities to manage the growing resource demand of urban dwellers. Incorporating carrying capacity and global ecological change considerations into city spatial planning and management is also needed for the development of sustainable human settlements. Cities depend on the surrounding environment and ecosystems to sustain life, health, security, and social cohesion and have no alternative than to create new (green and circular) economic opportunities that secure the long-term functioning of a city and quality livelihoods for its citizens, while addressing the unsustainable trends of the past.

One of the most notable values the Ecological Footprint adds to policy making is its ability to highlight trade-offs between competing human activities, which most other indicators track independently and in isolation. The results of this study allow city administrators to understand the high pressure that city residents place on natural resources, in absolute and relative Ecological Footprint terms. Unsustainable consumption patterns are identified as well as their drivers, pinpointing the policy and behavioural changes required to successfully transpose and implement several SDGs at the municipal level, and to make the city more resilient. The assessment of the Ecological Footprints of cities can help local governments meet a critical target of Agenda 2030 (SDG 12.8) regarding the need to have access to information and indicators that allow people to understand the complexity of the sustainable development challenge. But most importantly, it can foster a needed discussion on how to transpose Agenda 2030 to the city level and pinpoint which priorities and challenges local policies should look at. This is of particular importance in Portugal, where public debates on such issues remain in early stages.

Municipal leaders have to be aware of these critical leverage points to direct short-term, mid-term and long-term policies, reinforcing their role as critical drivers of behavioural change, while working in conjunction with the local population, public and private companies and other organizations to decrease the pressure on natural resources.

Footprint and biocapacity accounting are effective monitoring tools to assess medium- and long-term outcomes for overall progress towards sustainable development. Moreover, the simplicity of Footprint communication and its visual nature make it a powerful tool to raise awareness about the environmental consequences of resource consumption and policies that influence human demand on the planet. As an "early warning," these results can help instill holistic and long-term thinking among city leaders and stakeholders around resource use and overuse. As policies are implemented, short-term and issue-specific indicators tackling specific consumption activities, such as SDG indicators, are fundamental supplements to Ecological Footprint accounting.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2019.102442.

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