Environmental Impact Assessment Review 77 (2019) 136–144

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

Ecological footprint accounting: A multi-scale approach based on net primary productivity

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ARTICLE INFO

Keywords:
Multi-scale analysis
Ecological footprint accounting
Geographic scale
Territorial hectares
Net primary productivity
Equivalence factor
Yield factor
Remote sensing
GIS

ABSTRACT

The Ecological footprint accounting is a resource accounting tool that is used to track the sustainability of human systems. In this paper, we present a new approach to calculate the Ecological Footprint metrics at different geographic scales using Net Primary Productivity data. Our study focuses on the town of Afourar, Morocco, as a case study examined at three different scales; national, regional, and provincial scale. In contrast with other studies, our footprint accounting results are expressed in what we have called territorial hectares. The accounting results show that geographic scale has a significant influence on the footprint model, where three cases of sustainability were found. This implies that the efforts to maintain the sustainability of territories are more important at some scales than others. We argue that the relationship between sustainability and geographic scale is both strong and complex and that sustainability is a spatially relative concept. Therefore, we conclude that multi-scale analysis is crucial for making sustainable decisions and management policies.

1. Introduction

Urbanization has known a rapid historic transformation in the last centuries. Only 2% of the world population lived in urban areas in 1800, however, urban population increased to 14% in 1900, 29% in 1950, 47% in 2000, and exceeded 50% in 2008 (Wu et al., 2014). This trend is expected to rise in the future, and the world population is projected to be 100% urban by 2092 (Batty, 2011). Despite the dynamic symbiotic relationship between socioeconomic development and urbanization, the latter resulted in many environmental and socioeconomic problems (Grimm et al., 2008; Huang et al., 2015). As a result, the growing urbanization combined with the enormous overexploitation of natural resources has made the concept of 'urban sustainable development' the catchword of our time.

Sustainable development has been defined in many ways, the most widely quoted definition hails from "Brundtland "report: 'A development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987). It has also been widely accepted that sustainability is described in terms of three 'dimensions', 'pillars' or 'bottom lines'—environment, economy, and society—. The notion of sustainability assessment (sometimes referred to as sustainability accounting) has emerged from the need to ensure that territorial activities and planning contribute optimally to the achievement of sustainable development goals (Verheem, 2002). Parris and Kates (2003) proclaim that sustainability assessment has four fundamental purposes: (1) decision-making and management, (2) advocacy, (3) participation and consensus building, and (4) research and analysis.

The growing interest in the interaction between geographic scale and sustainability triggered a debate on whether cities (urban areas) or small towns (rural areas) are important in helping societies be more sustainable. This debate was the source of two fundamental notions known as "urban" and "rural" sustainability. Various studies have discussed the concept of urban sustainability over the last decades (e.g Alberti, 1996; Rees and Wackernagel, 1996; Newman, 1999; Wu, 2010; Mori and Christodoulou, 2012). However, rural sustainability remains less abundant in sustainability literature and is just beginning to attract the attention of researchers and policy-makers. Visvaldis et al. (2013) argue that modern regional development agendas are greatly focusing on large cities while, in fact, small towns —rural areas— play an even more important role in society than urban areas through urban-rural interactions (such as transportation, tourism, community development, agriculture, and culture) and supported the development of urban communities in the past.

The spatial dimension of sustainability was admitted to have a significant effect on the process of sustainability assessment, on territorial management and monitoring policies, and the decision-making process. Numerous studies have questioned the relationship between

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https://doi.org/10.1016/j.eiar.2018.12.003
Received 27 February 2018; Received in revised form 4 November 2018; Accepted 17 December 2018

scale, sustainability, and territory management (see: Wilbanks, 2007; Huang et al., 2015; Galli et al., 2016; Dor and Kissinger, 2017). The consideration of the spatial component in sustainability accounting was also admitted not only to help understand spatial transitions and their impacts, but also to present potential management scenarios which can help determine the kind of actions that should be taken on each geographic scale and the way these actions affect each-other (Wilbanks, 2007). As a result, many studies recommended using multi-scale approaches to deal with spatial heterogeneities when assessing the sustainability of human systems (Wilbanks, 2007; Coenen et al., 2012; Huang et al., 2015; Galli et al., 2016; Dor and Kissinger, 2017).

In addition to the spatial dimension of sustainability, proposed methods and approaches to evaluate the sustainability of human systems were found to play a crucial role in the process of sustainability assessment. Different accounting approaches are found in the literature (see: Lamberton, 2005; Pope et al., 2004). The indicator-based approach remains the most practical and widely used to assess sustainability (Hemphill et al., 2004). This approach is founded on what we know as 'sustainability indicators' which can be defined as sets of parameters or integrated-associated parameters devoted to measure the progress of societies in terms of sustainability (Gallopin, 1997; Shen et al., 2011). Yet, choosing which indicator to use remains strongly linked to how we define sustainability (Huang et al., 2015). One tool being used more and more to assess sustainability by measuring and comparing the appropriation of natural resources to the generative capacity of bioproductive areas is known as the Ecological Footprint Accounting (hereafter EFA).

The accountability of the footprint model is expressed by means of two metrics known as the Ecological Footprint and the Biocapacity (henceforth EF and BC). EF measures the human appropriation of natural resources, while BC represents the bio-productive capacity of bioproductive areas to generate the resources we need and to absorb the waste we generate (Rees, 1992; Rees and Wackernagel, 1996; Wackernagel et al., 1999a, 1999b; Kitzes et al., 2007). The accounting results can be expressed either in Global hectares (Gh) or Local hectares (Lh). Results expressed in Gh give us an idea about the amount of the planet's regenerative capacity that is being used by a given human system, whereas those expressed in Lh enable us to determine the amount of bioproductive lands used by a given human activity or population (Kitzes et al., 2009a, 2009b).

These two units are limited to a single spatial context which limits their applicability to the management of sub-national territories. On the one hand, global footprint accountings do not seem to have a spatially factual sense when applied to sub-national contexts. According to Wiedmann and Lenzen (2007), global accountings are primarily applicable to cross-national comparisons and have a limit aptitude to answer regional research or policy questions. On the other hand, Local footprint accountings lack spatial significance because they exclude normalizing parameters (see: Erb, 2004 and Kitzes et al., 2009a) whose importance manifests in their ability to rationalize the aggregation of the different land categories (Wackernagel et al., 1999a; Galli et al., 2007). Besides, a number of studies state that EFA is sensitive to these parameters and their exclusion would affect the significance and reliability of the EFA results (see: Van Vuuren and Smeets, 2000; Haberl et al., 2001; Van Vuuren and Bouwman, 2005).

EFA has been applied to both urban and suburban areas and it was used to study systems of different scopes (see: Wackernagel, 1998; Muñiz and Galindo, 2005; Kitzes et al., 2007; Flint, 2001; Toderoiu, 2010; Yue et al., 2012; Li et al., 2016; Dor and Kissinger, 2017) and was subject to continuous development resulting in new methodologies and approaches (see: Gössling et al., 2002; Scotti et al., 2009; Galli et al., 2011; Čuček et al., 2012). The inclusion of spatial data and methods in the footprint model is one of its major aspects of development. A number of studies have demonstrated the compatibility of this model with remote sensing data and GIS techniques. Their usefulness is manifested in their aptitude to reduce data gaps from which the majority of sustainability assessment tools suffer, in addition to their help in monitoring spatiotemporal irregularities and predicting future tendencies (e.g. Chang and Xiong, 2005; Yue et al., 2006; Yue et al., 2012; Schatz et al., 2013; Li et al., 2016;).

The footprint model has also shown compatibility with numerous types of spatial models and datasets. The incorporation of Net Primary Productivity (NPP) is one of the widely discussed aspects of development of this model. According to Haberl et al. (2004), there is a considerable similarity between the characteristics of the footprint analysis and NPP. This similarity manifests in the aptitude of NPP to simulate the productivity and regenerative capacity of ecosystems and its ability to represent an important link between atmosphere, biosphere, and human activities (Raich et al., 1991; Scurlock and Olson, 2002). While multiple studies have discussed the synergies and trade-offs between NPP and the footprint model (see: Haberl et al., 2004; Venetoulis and Talberth, 2008; Kitzes et al., 2009b; Siche et al., 2010; Yin et al., 2017), others have used NPP to calculate some key parameters of the footprint model (e.g.: Gu et al., 2015 and Moucheng et al., 2015). However, the compatibility of this parameter with the footprint model has been criticized for the way NPP measurements represent total terrestrial productivity rather than the one used to directly sustain human activities (see: Kitzes et al., 2009a; Ewing et al., 2010; Yin et al., 2017).

This paper presents a new method to calculate the EFA metrics at multiple scales through the example of a Moroccan town called Afourar which has been studied at the national, regional, and provincial scale. It uses NPP as a base of calculation, introduces a more spatially flexible alternative to Gh and Lh units, and investigates the relationship between scale, sustainability, decision and policy-making process through the evaluation of the effect of scale variation both on the EFA results and the decision and policy-making process.

2. Materialsandmethods

2.1. Case study

The Moroccan town Afourar is located at the northern edge of Azilal province (32° 12′ 36“ N latitude and −6° 30′ 00” W longitude) which is part of Beni-Mellal Khenifra region (Fig. 1). The population of this town is estimated to 34,119 inhabitants and characterized by a young population (HCP, RGPH, 2014). The abundance of water resources, the fertility of the soil, and the diversity of the relief have made agriculture the main economic activity of the town (85% of the total area of the town is devoted to agriculture activities).

2.2. Methods

In this paper, we suggest a more general footprint accounting method that accounts for two spatial units. The first is called 'study area' and it corresponds to the subject area of assessment. The second is 'reference area' and it denotes the territory according to which our calculation and comparison of results are carried out. The accounting results will, therefore, be expressed in what we have called "territorial hectares" (Th); hectares normalized to have a given reference area's (territory) average bioproductivity. This unit corresponds, in fact, to the notion of global hectares restricted to a reference area and represents a more adaptive and flexible spatial unit that is suitable for multi and cross-scale analyses.

The territorial approach described in this study represents a more general approach to calculate the footprint metrics at multiple scales. An overview of some of the major differences between this territorial approach and the global and local footprint approaches is resumed in the following Table 1.

Our approach only remains valid and rational if we take into account three main points. The first point concerns normalizing factors and states that their calculation should be performed in consideration of the average productivity of a selected reference area. Consequently,

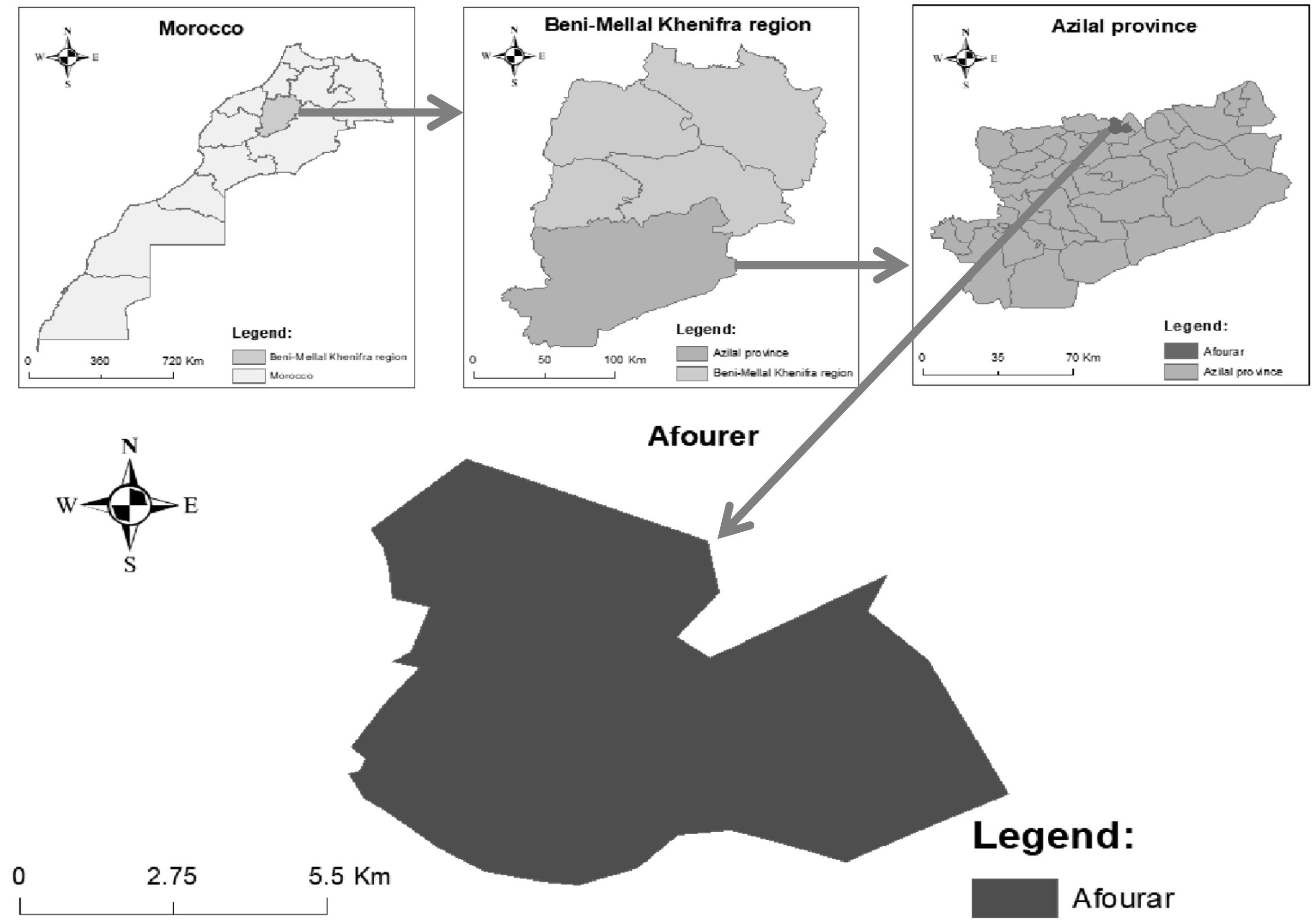

Fig. 1. Geographic situation of our study area

these parameters become invalid and should be recalculated if we change the reference area. The second point is related to the significance of results expressed in territorial hectares (Th). The notion of 'territory' used in our study is equivalent of that of reference area (we also refer to it sometimes as spatial scale or context) according to which our footprint analysis is performed. The width of a territory can range from global to local scales. Consequently, if we consider the spatial variability and disparities in land properties, performing an EFA of a given study area at different scales would result in new spatial units each time the scale changes. In other words, by performing a footprint accounting at the global scale, the results would be expressed in Global hectares, but at a national scale, the accounting results would be expressed in national hectares. Likewise, accountings performed at a regional scale would be expressed in regional hectares, and those carried out at a local scale would then be expressed in local hectares. Correspondingly, and with regards to the definition of 'territory' in our study, the general expression would then be: "when a footprint accounting of a certain study area is performed at a given territory, the accounting results would then be expressed in Territorial hectares". The third and last point concerns the analysis and interpretation of Th results, and here we insist that comparison and interpretation of results should be done within the same territory of analysis, that is to say we cannot compare the accounting results of two different study areas that exist within two different reference areas unless if they are being considered at a superior reference area (scale) that encompass them.

Concerning the calculation of the footprint metrics (EF and BC) of our study area, we first proceeded to calculate Yield and Equivalence factors for cropland, grazing land, and forest land at the three reference

Table 1
Major differences between Global, Local, and Territorial footprint accountings:

	Global footprint accounting (see Wackernagel et al., 1999band Kitzes et al., 2009b)	*Local footprint accounting* (see Kitzes et al., 2009aand Erb, 2004)	*Territorial footprint accounting*(this paper)
Research question	"How much of the planet's regenerative capacity is used by a specific human activity or population?"	"How much bioproductive area is used by a given human activity or population?"	"How much of a given territory's regenerative capacity is used by a specific human activity or population within that territory?"
Spatial applicability	Is applicable to global and national footprint accountings and focuses on cross-national comparison	Is only applicable to local footprint accountings	Is applicable to global, sub-global, and local footprint accounting and allows cross-scale analysis
Normalization factors	Are determined at the global scale	Aren't involved in the calculation of the footprint metrics	Are specific to each reference area (territory or scale)
Spatial unit	Global Hectares	Local Hectares	Territorial Hectares

Table 2
A suggested classification of vegetation types into the three categories of bioproductive areas.

Land category	Cropland	Grazing land	Forest land
Vegetation types	- Cropland or Natural vegetation - Croplands	- Grasslands - Permanent wetlands - Savannas - Closed Shrublands - Open Shrublands	- Mixed forest - Evergreen Broadleaf forest - Evergreen Needleleaf forest - Woody Savannas

areas of our study. We subsequently calculated the harvested areas and determined the areas of the bioproductive lands (built-up area, croplands, forest land, and grazing land). Eventually, we determined EF, BC, and the ecological balance (EB) of our study area at the three reference areas (national, regional, and provincial scales).

2.2.1. Yield factors

The original definition of Yield Factors (YFs) introduces it as the relative productivity of national and world average hectares of a given land use type used to compare the national average yield per hectare and the world average yield for the same land category (Kitzes et al., 2007; Li et al., 2016). However, that definition remains valid only for national footprint accounting and thus applying it to a local study case will lead up to ignoring the variability of environmental conditions and the availability of bioproductive lands (Van den Bergh and Verbruggen, 1999), which strongly affects the reliability of the footprint accounting results.

In this study, we adapted the YFs equations given by Lin et al. (2016) to sub-global and local case studies by declaring it as the relative productivity of a study area and the average hectares of a given land use type at a given reference area. For land categories that produce one primary product such as grazing land, forest land, and fishing land, we suggest YFs to be calculated as follows:

$$\boldsymbol{YF}_{RA}^{L} = \frac{\boldsymbol{Y}_{SA}^{L}}{\boldsymbol{Y}_{RA}^{L}}$$

Where

$\boldsymbol{YF_{RA}}^{\boldsymbol{L}}$: Yield factor of a land category (L) calculated at a given reference area (RA), (1).

$\boldsymbol{Y_{SA}}^{\boldsymbol{L}}$: Average yield for a given study area (SA) and a land category (L), (t. ha − 1).

$\boldsymbol{Y_{RA}}^{\boldsymbol{L}}$: Average yield for a given reference area (RA) and a land category (L), (t. ha − 1).

However, the YF of croplands can't be calculated similarly to the other land categories for the simple reason that it produces more than one primary product. Therefore, it must be calculated in a way that aggregates YFs of the different primary products using an area-based weighting:

$$\mathbf{YF}_{\mathrm{RA}} = \frac{\sum \mathbf{YF}_{\mathrm{RA}}^{\ \mathrm{i}} *\mathbf{A_i}}{\sum \mathbf{A_i}}$$

Where

$\boldsymbol{YF_{RA}}$: Cropland Yield factor calculated at a given reference area (RA), (1).

$\boldsymbol{A_i}$: Crop area of a product (i), (ha).

$\boldsymbol{YF_{RA}}^{\boldsymbol{i}}$:Yield factor of a product (***i***) calculated at a given reference area (RA), (1).

2.2.2. Equivalence factors

Equivalence factors (EQFs) are standardizing factors that help translate the area supplied or demanded of a specific land-use type into units of average biologically productive area in order to assemble different area types with different productivities. The calculation of EQFs can be achieved through two methods (Moucheng et al., 2015). The first method is primarily used to calculate global EQFs used in global footprint accountings. It is founded on suitability indexes that can be determined by combining data provided by FAO Global Agro-Ecological Zones (GAEZ) and actual information about cropland, forest, and grazing areas from FAOSTAT (Wackernagel et al., 2002a; Kitzes et al., 2009b; Lin et al., 2016). The second calculation method of EQFs was initially introduced by Venetoulis and Talberth (2008) and developed by Moucheng et al. (2015). It uses Net Primary Productivity data that can be either extracted from satellite-derived products (such as MODIS NPP product), or estimated using different types of physical and biophysical parameters, to calculate Equivalence factors at any temporal and spatial scale.

According to Ruimy et al. (1994), NPP estimation models can be divided into three major categories: (1) parameter models or literature data of NPP for major ecosystem types; (2) statistical models, and (3) process-based models. In this study, we used a process-based model called Carnegie–Ames–Stanford Approach (CASA) that was introduced by Potter et al. (1993) and developed by Field et al. (1995). The CASA model combines ecological principles, remote sensing data, GIS modeling, and earth surface data to estimate terrestrial NPP on a given time step (see: Potter et al., 1993; Nayak et al., 2010; Huang et al., 2012; Bao et al., 2016). Our choice of this model took consideration of three factors; (1) its simplicity and integration of a variety of environmental and parameters, (2) the possibility to estimate NPP for different vegetation types, and (3) its spatial and temporal flexibility.

The calculation method suggested by Moucheng et al. (2015) has some ambiguities regarding the classification of areas into major categories of bioproductive areas (cropland, grazing land, fishing land, and forest land). Accordingly, we propose an intermediate stage between the modeling of NPP and the calculation of EQFs using the equations described in Moucheng et al. (2015) (see the equations below). This stage consists of aggregating vegetation types that exist within each of our reference areas into three categories of bioproductive lands (Table 2).

$$\boldsymbol{EQF}_{RA}^{\ L} = \frac{\boldsymbol{NPP}_{RA}^{\ L}}{\boldsymbol{NPP_{RA}}} \ \textbf{Where}: \boldsymbol{NPP}_{RA} = \frac{\sum \boldsymbol{NPP}_{RA}^{\ L} *\boldsymbol{A_L}}{\sum \boldsymbol{A_{L.}}}$$

Where

$\boldsymbol{EQF_{RA}}^{\boldsymbol{L}}$: Equivalence factor of a land category (L) at a given reference area (RA), (1)

$\boldsymbol{NPP_{RA}}^{\boldsymbol{L}}$: NPP of a given reference area (RA) and land category (L), (gC.m − 2)

$\boldsymbol{NPP_{RA}}$: Average NPP of all land categories at a given reference area (RA), (gC.m − 2)

$\boldsymbol{A_L}$: Area of a land category, (m2)

2.2.3. Harvested areas

The harvested area (HA) of a given land type stands for the amount of consumed land product type converted into an area unit that presents the bioproductive area required to support the needs of a given human activity or individuals (Galli et al., 2007; Scotti et al., 2009). This conversion was fulfilled by dividing the amount of consumed products by their local average yields:

$$\mathrm{HA}_{\ \mathrm{RA}}^{\ \mathrm{i}} = \frac{\mathrm{C_i}}{\mathrm{Y}_{\mathrm{SA}}^{\ \mathrm{i}}}$$

Where

$\boldsymbol{HA_{RA}}^{\boldsymbol{i}}$: Harvested area of a product (i) at a given reference area (RA), (ha)

$\boldsymbol{C_i}$: The amount of each product (i) consumed by the population of our study area, (t)

$\boldsymbol{Y_{SA}}^{\boldsymbol{i}}$: Average yield for a given study area (SA) and product(i), (t. ha-1)

2.2.4. The area of bioproductive lands and built-up area

In order to determine the area of bio-productive lands, we used a high-resolution satellite image (sentinel-2 product). While the forest and cropland categories were easy to identify, the built-up area and grazing land categories represented an exception and required further considerations. The surface elements that were labeled as built-up-area are Infrastructure for housing, transportation, industrial spaces (hydroelectric dams and reservoirs that used for the production of hydropower), and water canals that are used to irrigate crops. The area of grazing lands category was defined as the vegetated land that is suitable for grazing by livestock. It was determined using a Normalized Difference Vegetation Index (NDVI) map of the greenest month of the year (April).

2.2.5. Calculation of the footprint metrics

After determining the input parameters, we proceeded to calculate EF and BC of Cropland, Grazing land, Forest land, Carbon land, and Built-up area.

- Calculation EF:

The EF of our study area was calculated by summarizing the five footprints (Cropland, Grazing land, Forest land, Carbon land, and Built-up land) for each of our three reference areas:

$$\mathrm{EF_{RA}} = \sum \mathrm{HA_i} * \mathrm{YF_{RA}^{L}} * \mathrm{EQF_{RA}^{L}}$$

Where

EF_{RA}: Ecological footprint calculated at a given reference area (RA), (Tha)

$HA_{RA}{}^{i}$: Harvested area of a product (i) determined for given reference area (RA), (ha)

$YF_{RA}{}^{L}$: Yield factor of a land category (L) calculated at a given reference area (RA), (1)

$EQF_{RA}{}^{L}$: Equivalence factor of a land category (L) calculated at a given reference area (RA), (1)

- Calculation BC:

Likewise, we calculated BC of Afourar by summarizing the biocapacities of the three bioproductive lands (cropland, grazing land, and forest land) for each of our three reference areas:

$$\mathrm{BC_{RA}} = \sum \mathrm{A_L} * \mathrm{YF_{RA,L}} * \mathrm{EQF_{RA,L}}$$

Where

BC_{RA}: Biocapacity calculated at a given reference area (RA), (Tha)

A_{L}: Area of a land category (L), (ha)

$YF_{RA}{}^{L}$: Yield factor of a land category (L) calculated at a given reference area (RA), (1)

$EQF_{RA}{}^{L}$: Equivalence factor of a land category (L) calculated at a given reference area (RA), (1)

Consistent with the recommendation of previous studies (e.g. Li et al., 2016; Yue et al., 2012; Vačkář, 2012; Wackernagel et al., 1999a), we deducted 12% of the total BC for the conservation of biodiversity. The remaining portion was used to calculate EB.

- Calculation of Ecological Balance:

As a final stage, we calculated the ecological balance (EB) of our study area at each of the three reference area. We assume that our study area is sustainable if its overall BC is greater than or equal to EF implying that it has an ecological reserve (EB $\geq$ 0), while we consider it unsustainable if its overall BC is less than EF and we say that it has an ecological deficit or overshoot (EB $<$ 0). Our study area's EB was calculated for each reference area as follows:

$$\mathrm{EB_{RA}} = \mathrm{BC_{RA}} - \mathrm{EF_{RA}}$$

Where

EB_{RA}: is the ecological balance at a given reference area (RA), (Tha)

BC_{RA}: is the Biocapacity at a given reference area (RA), (Tha)

EF_{RA}: is the Ecological Footprint at a given reference area (RA), (Tha)

2.3. Data sources

In this study, data collection was performed at four spatial levels (national, regional, provincial, and local scale) and focused on three categories of data: (1) Consumption data, (2) Average yield (3) and auxiliary data (Remote sensing and climate data used to determine the area of bioproductive lands and to estimate NPP).

2.3.1. Consumption data

Consumption data was collected using a top-down strategy. It consisted of collecting consumption data of primary products such as: (1) foodstuffs (vegetables, fruits, cereals, and meat), (2) Wood, and (4) fuel products (Gasoil, and Diesel), collected from their vendors and consumers, in addition to the administrations in charge of managing these products.

2.3.2. Average yields

National, regional, provincial and local yields of consumed products were required to calculate YFs and HAs. We used data collected from different administrations (ORMVAT, DRA, DREF, and HCEFLCD) to assure the highest degree of reproducibility and reliability of our results.

2.3.3. Spatial data

- Area of bioproductive lands:

The area of Bioproductive lands was determined by using two satellite images from two different dates (August, and April). The image of August was used to avoid the spectral nuisance of seasonal vegetation while determining the area of built-up land, in contrast, that of April was used to determine the area of grazing land.

- Net Primary Productivity:

Regarding the modeling of NPP, several datasets were required to run the CASA model to generate monthly NPP maps that were summed up to obtain NPP of our year of study (2016). The required dataset consisted of MODIS products (Fraction of Absorbed Photosynthetically Active Radiation (FPAR), surface reflectance images, and Land cover product) and meteorological data (temperature and solar irradiance). The properties of the maps we used as input for our model are described in Table 3.

Table 3

Characteristics of the input data of CASA-model.

Model Parameters	Spatial		Temporal	
	Resolution	Extent	Frequency	Extent
FPAR	500 m	Morocco	Monthly	2016
Solar irradiance	500 m	Morocco	Monthly	2016
Temperature	500 m	Morocco	Monthly	2016
surface reflectance	500 m	Morocco	Monthly	2016
Land cover map	500 m	Morocco	Annual	2016

Table 4
Results of EQFs and YFs calculation.

	EQF			YF		
	Cropland	Grazing land	Forest land	Cropland	Grazing land	Forest land
National	1.974	0.610	2.440	0.941	1.726	0.004
Regional	1.642	0.681	1.849	1.442	1.167	0.011
Provincial	2.270	0.844	2.201	1.481	3.316	0.659

Table 5
the footprint metrics expressed in Territorial hectares per-capita.

	National	*Regional*	*Provincial*
EF	*0.639*	*0.648*	*1.793*
BC	*0.449*	*0.570*	*0.836*
EB	*−0.190*	*−0.078*	*−0.957*

3. Results

3.1. Equivalence and yield factors

The calculation of Equivalence and yield factors was performed at three spatial scales. The results revealed a high sensitivity of these factors to scale variation (see Table 4). Regarding EQFs, overall results show that the national and provincial scale represented the highest values EQFs, whereas the category of forest land presented the highest values followed by cropland then grazing land categories. In the same manner, overall YFs results show a strong disparity at each of the reference areas. In terms of land categories, the category of grazing land presented the highest values, especially at the provincial scale, whereas the cropland category has shown relatively high values and surpassed that of grazing land at the regional scale. YF of forest land presented the weakest values at each of the three scales. The spatial variability of EQFs and YFs could be the result of the difference in lands properties and environmental conditions at each of the three scales used in our study.

3.2. Footprint metrics

It can be seen from overall per capita results of EF and BC (Table 5) that changing reference area has a significant impact on the footprint accounting results, which implies that EFA is very sensitive to scale variation. In terms of demand, EF remained almost the same at the regional and national scales, while it was highest at the provincial scale. As for supply, BC has evolved contrastingly with the width of scale and was highest at the provincial scale.

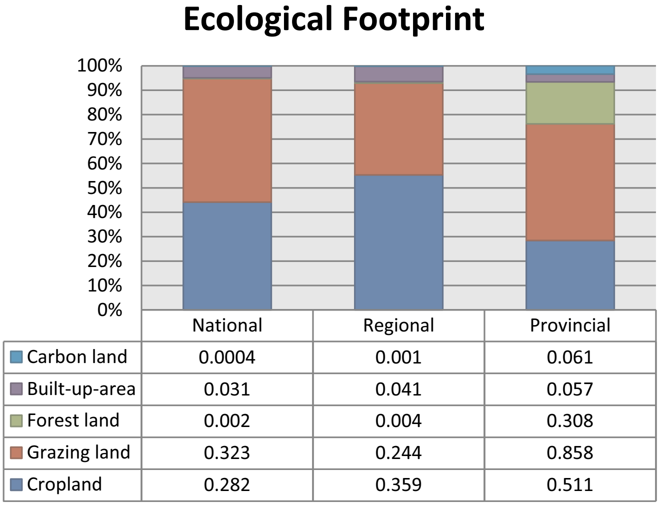

Fig. 2. Proportions of EF components expressed in Territorial hectares per-capita

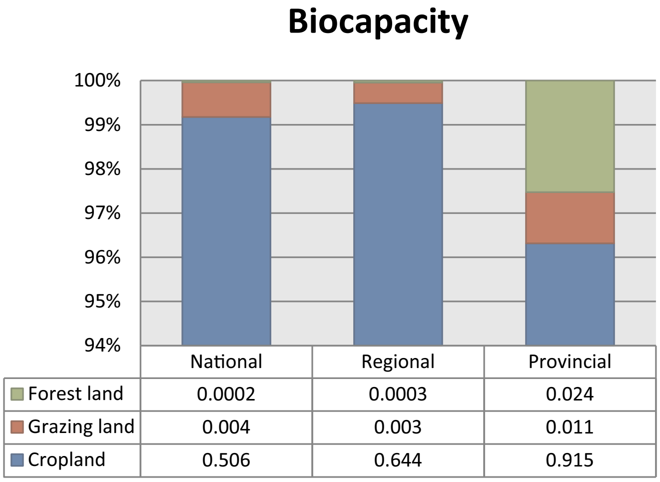

Fig. 3. Proportions of BC components expressed in Territorial hectares per-capita.

By comparing EF with BC, and as a result of the spatial variation of these metrics, the ecological balance (EB) has also shown an evident response to the variation of scale, whereas our study area has shown three different cases of ecological deficit that do not seem to follow the spatial ordering of reference areas. At the national scale, the ecological deficit per capita was equal to −0.190 Th, while it was minimized at the regional scale where EF exceeded BC by 0.078 Th and maximized at the provincial scale where EF surpassed BC with 0.957 Th.

3.3. Proportion of EF and BC

The proportions of land-use types of the study area in Fig. 2 and 3 show that both EF and BC components were also affected by the spatial dynamics that manifested in our multi-scale analysis. In terms of EF (Fig. 2), the proportion of the five land use categories of EF (carbon land, built-up-area, forest land, grazing land, and cropland) changed differently over the three spatial contexts of our study. The categories of grazing and cropland predominated at the national and regional scales, while the category of built-up-area was relatively minimized at the three scales and has known a slight decrease at the provincial scale. The carbon and forest land category were disregarded at the national and regional scale while they have shown an increase at the provincial scale, especially for the category of forest land.

With regards to BC (Fig. 3), the three categories of land use (cropland, grazing land, and forest land) have shown a different response to scale variations. The category of cropland was significantly predominant at the national and regional scale while it has slightly decreased at the provincial scale. The other categories (grazing and forest land) were proportionally the weakest at the three given scales. While forest land category has shown a remarkable increase at the provincial scale compared to the grazing land category.

4. Discussion

The findings of this study affirm the efficiency of multi-scale analysis and its contribution to the policy and decision-making process. Also, multi-scale analysis seems not only help decrease restrictions related to the nested environmental limits and the difficulty to keep track of resource exchanges, but it also presents an opportunity to confirm the importance of geographic scale, which was previously discussed in the literature (e.g. Fresco and Kroonenberg, 1992, Wilbanks, 2006, Wilbanks, 2010, Willbanks 2011).

As evidenced by this study, performing EFA calculations at different geographic scales resulted in considerably different results. The difference in results has evidenced in both the overall footprint metrics (Table 5) and the proportion of their components (Figs. 2 and 3). The acquired results demonstrated that assessment results might not follow the spatial hierarchy of the considered reference areas. This comes in accordance with Fresco and Kroonenberg (1992) who argue that sustainability may display discontinued or irrespective responses to scale variation in spite of its reliance on geographic scale. We also argue that it is not possible to predict how the accounting results would be like if we enlarged or reduced the extent of our reference area, and we are unable to say how these results would be if we considered a different study area at the same reference areas, or if the same area was considered at other reference areas that reflect different land properties. We relate this uncertainty to the heterogeneous repartition, proportion, and productivity of lands in space and time.

Methodologically speaking, normalizing factors represented the essence of the spatial interaction between the study area and the spatial context of the footprint analysis and were the reason behind the spatial disparity of our results (Table 4). According to Monfreda et al. (2004), these factors have not been satisfactory developed and they do not represent the productivity of all types of land. Yield factors have received little methodological criticism in the literature; however, the calculation of Equivalence factors represented an exception and could be calculated using two approaches that use different datasets (see: Venetoulis and Talberth, 2008). The first approach is said EF-GAEZ, it is used primarily by the GFN to perform global and national footprint accounting and it is exclusive to bioproductive lands that are directly used by humans. The second approach is referred to as EF-NPP and is inclusive of all land types and productivity. Proponents of the first approach do not deny the usefulness of the NPP based approach, but rather, they criticize its utilization for being holistic by involving areas that are not used directly useful for human activities (e.g.: Erwin et al., 2010 and Kitzes et al., 2009b). On the other hand, proponents of the second approach argue that all types of land should be involved considering their important role in assimilating our wastes, generating global biocapacity, and supporting critical ecosystem services that are crucial for both human and non-human life (e.g.: Venetoulis and Talberth, 2008 and Haberl et al., 2004). While both points of view have merit, we suggested a way to cope with this controversy by estimating NPP for different vegetation types and classifying them into categories of land use (grazing land, cropland, fishing land, and forest land) based on their relevance to direct human utilization, which represents a way of combining principles of the EF-GAEZ approach and the data used by the EF-NPP approach. Using the classification suggested in Table 2 and the calculation method suggested by Moucheng et al. (2015), the calculation of EQF has shown consistency with the logical ordering of bioproductive lands based on their potential productivity. For instance, EQFs of grazing lands represented the lowest value among the other land categories (Table 4). This result sounds reasonable if we take into account the rationale behind EQFs and the simple fact that this category of land is generally characterized by a low productivity compared to other terrestrial bioproductive lands (Croplands and forest lands). Possible shortcomings of our method would then be associated with the way vegetation types are aggregated. Also, it is worth mentioning that any addition, deletion, or modification of these vegetation types would have a significant impact on EQFs and thus on the footprint accounting results.

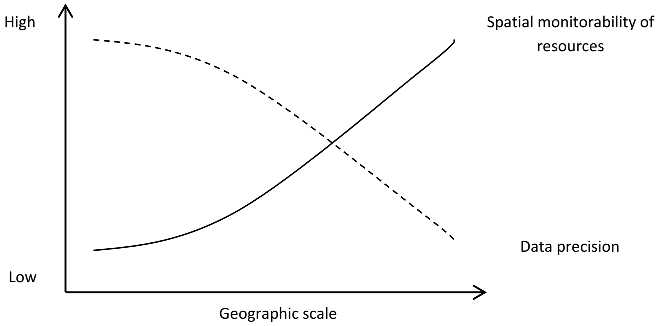

Fig. 4. the relationship between of scale variation, data precision, and resource monitorability

Regarding the importance of geographic scale in the sustainability assessment process, we believe that all scales are of equal importance to the sustainability assessment process. A consideration of large scales is crucial because exchanges between territories and their environment are more important than those at smaller scales, and also because assessments carried at large scales help us have a clearer overview and a high spatial monitorability of resource exchanges between territories. However, this high monitorability comes at the cost of losing locally important information. As a result, we tend to find some territories either very (un)sustainable when considered at larger scales. On the other hand, smaller scales enable us to have a more accurate and precise overview on the natural capital of our study areas in term of quantitative and qualitative data while they restrict the spatial monitorability of resource exchanges. In order to better perceive the potentials and weaknesses represented by each spatial level, we present an illustration of the paradoxical relationship between the width of geographic scale, the spatial monitorability of resource exchanges, and the precision and accuracy of datasets in Fig. 4. In the light of the above overlaps, we believe that multi-scale analysis is strongly required in sustainability assessments owing to (1) its aptitude to help us monitor resource exchanges at different spatial levels, (2) its usefulness in understanding the interaction between territories and their environment, (3) its contribution to a better understanding of the relationship between geographic scale and sustainability, and (4) its usefulness in the policy- and decision-making process.

Beside its potential to help us study the complexity of the relationship scale- sustainability relationship, multi-scale analysis can also be used as a supporting tool that helps sort and compare urban or rural areas that exist within the spatial context of study (what we have called a reference area in our study) according to the resources and the bioproductive capacity of this context. To put it another way, and using the example of the Footprint model studied in this paper, multi-scale footprint analysis can serve as a means of sorting, comparing, and prioritizing territories in terms of sustainability performance. As a result, and in line with what came in Galli et al. (2016) and Dor and Kissinger (2017), multi-scaling the footprint analysis would be a great help to national and regional decision-makers and policy practitioners, who are considered the end users of this model, by helping them have an inclusive insight and monitoring of their territories of action and develop more effective decisions and management policies.

The involvement of remote sensing and GIS modeling in our multi-scale footprint analysis has shown their considerable applicability in the sustainability assessment process. Their utility manifests in their potential help to reduce data gaps, which Visvaldis et al. (2013) argue that the majority of sustainability assessment approaches and indicators suffer from, and their contribution to the monitoring of spatiotemporal irregularities and prediction of future tendencies (see: Chang and Xiong, 2005; Yue et al., 2006). The usefulness of remote sensing and

GIS in our study has evidenced in four fundamental applications; (1) the determination of areas of bioproductive lands, (2) the estimation of NPP, and (3) the spatialization of the process of sustainability assessment through the example of EFA.

As for the case study analyzed in this paper, the town of Afourar displayed three different cases of unsustainability during the year 2016 (Table 5). It was closest to sustainability at the regional scale, while it was unsustainable at the national context and very unsustainable at the provincial scale. The variability of these results would certainly be translated into a variety of decisions and policies made at each of the three spatial contexts of study. This is because the spatial dimension of sustainability is also an influencing factor in how and where decisions are made. We also believe that these different results would lead up to contradicting decisions and policies if they are made at each spatial context and without any consideration of other superior or inferior contexts. Conversely, they would lead up to more effective and reasonable decisions and policies if the three contexts are considered simultaneously.

As for the limitations of this study, some of the land-use components were not considered in our footprint calculations either because they did not exist within our study area or as a way to simplify the footprint model. These limitations can be determined in two points: (1) our study area did not contain any fishing grounds (no Fish farms, or natural water bodies devoted to fishing), and all the water bodies that exist within it are limited to hydropower production and irrigation, which signifies that fishing ground category was not considered in calculations and was considered null. (2) A literature review revealed the existence of another Biocapacity component related to infrastructure (e.g., Borucke et al., 2013 and Lin et al., 2016), however, we labeled infrastructure as a built-up area, and we did not consider it in our Biocapacity calculation as a simplification of our model. On the other hand, the unavailability of some land-productivity data during the year of our study (2016) forced us to use data from previous years as a substitute, for example, in the case of national forest yield, we used the average production of timber from the Moroccan Forestry Administration (Eauxetforets.gov.ma, 2017), while the data of consumed cropland products were limited to some of the very commonly consumed cropland products by the inhabitants of the town (cereals, olives, and vegetables).

5. Conclusion

Admittedly, the spatialization of sustainability has proven that the relationship between sustainability and geographic scale is both strong and complex. Not only has the nature of this relationship been demonstrated, but also the relativity of the concept of sustainability to the territory of assessment.

Multi-scaling the Footprint accounting approach helps visualize the relationship between sustainability and geographic scale. In spite of the spatial hierarchy of our calculations, the results and discussion held in this paper proved that the nature of this relationship is rather complex than deterministic.

As for the case study analyzed in this paper, and in terms of decision-making and territorial management policies, the town should be more prioritized at the provincial scale than the national and regional scales to achieve the targeted sustainability.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2018.12.003.

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