Ecological Indicators 124 (2021) 107439

Contents lists available at ScienceDirect

Ecological Indicators

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

Comparison of two biophysical indicators under different landscape complexity

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ARTICLE INFO

Keywords:
Ecological footprint
Energy-landscape integrated analysis
Socio-metabolic system approach
Biophysical sustainability metrics
Iran

ABSTRACT

Ecological Footprint (EF) and Energy-Landscape Integrated Analysis (ELIA) estimate human societies' imprint on nature. Both methods aim to provide overviews regarding biophysical society–nature interactions. The purposes of this article are to compare how EF and ELIA conceptualize human-nature relationships, and what results they produce when applied to the same landscape scale, in order to consider how their methodological similarities and differences can account for Land Use and Cover Change (LUCC). This conceptual comparison acknowledges the "ecocentric" perspective of EF adopted to relate end consumption baskets of human populations with the land biocapacities, and the "social metabolism" perspective of ELIA to take into account biophysical transformations and spatial distribution of matter-energy flows in different land uses. The two methods were applied to a case study of 46 municipalities in the Qazvin Province (Iran). These municipalities were grouped according to the values of the two methods by cluster analysis and correlated with landscape heterogeneity. The correlation analysis demonstrates that EF and ELIA indicators only overlap when landscape structure is highly simplified. However, lower accuracy of EF compared to ELIA as an indicator of socioecological impacts of different types of agricultural practices is confirmed. Although EF remains a useful indicator of unequal appropriation of Earth's biocapacity, it does so by taking average patterns of food production and consumption as given. To distinguish environmentally friendly from degrading practices, more precise indicators at the landscape level such as ELIA are required for farmers, consumers and policymakers to choose more sustainable options in their decisions.

1. Introduction

Different indicators have been developed in response to the need to measure and evaluate the negative impacts of human activities on the biosphere (Darvishi et al., 2020c; Jóhannesson et al., 2018), whose accuracy and usefulness depend on how each approach conceptualizes society-nature relationships (Ostrom, 2009; Binder et al., 2013). Any advance in the indicators used in the sustainability assessment contributes to improving the understanding of complex socio-ecological systems and helps increase the awareness and will of citizens, farmers, land-use planners and policy-makers to move forward new sustainability-oriented initiatives (Steffen et al., 2015; Raworth, 2017; O'Neill et al., 2018; Darvishi et al., 2020b). Some of these assessment methods focus on material, energy and socioeconomic flows (Binder et al., 2013), together with their impacts on Land Use and Cover Change (LUCC) (Darvishi et al., 2015a; 2015b). The Ecological Footprint (EF) focuses on the unequal appropriation of the biological productive areas required for each material or energy used to provide consumable goods to society, and to absorb the corresponding greenhouse gas emissions (Rees, 1992; Wackernagel and Rees, 1996; Hoekstra, 2009; de Alvarenga et al., 2012; Mousavi and Falahatkar, 2020; Shahzad et al., 2021).

The EF has become a widely used but controversial biophysical indicator that has long been debated in Ecological Economics and Sustainability Science (Shahzad et al., 2021). Criticisms have focused on three main aspects: 1) turning socioecological impacts, which are multidimensional and multi-scalar in nature, into a single unit such as hectares of global terrestrial biocapacity; 2) adding these different types of hectares –forest, cropland and pasture, marine fisheries, energy carbon footprint and built-up land— which have a very different real entity and meaning; and 3) in order to make these results comparable,

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https://doi.org/10.1016/j.ecolind.2021.107439
Received 25 August 2020; Received in revised form 12 November 2020; Accepted 18 January 2021
Available online 4 February 2021

counting the EF aggregates and their sub-indicators with global averages in per capita terms that convert even the most realistic components of those hectares into virtual spaces (van den Bergh and Verbruggen, 1999; Ayres, 2000; Opschoor, 2000; Wiedmann and Lenzen, 2007; Fiala, 2008; Giampietro and Saltelli, 2014).

According to critics, these methodological choices make EF an inaccurate indicator of environmental impacts. The energy footprint is measured by the virtual hectares of average forest surfaces that would had been required to absorb current global Carbon emissions, although they do not exist for the most part. Indeed, within the EF framework the main warning about overshooting planetary limits mainly depends on the global increase of these virtual hectares of Carbon footprint (van den Bergh and Verbruggen, 1999; Giampietro and Saltelli, 2014). Food and fibre footprints are considered regardless of the type of agriculture practiced. Organic agriculture and extensive livestock farming may require more land per unit of final product, which increases their EF compared to polluting industrial agriculture and feedlots (Lenzen et al., 2007). This paradox comes from a resource-to-land conversion that cannot register different intensities of land uses or in human appropriation of net primary production (Monfreda et al., 2004; Haberl et al., 2004; Ferng, 2007). Therefore, EF are calculated without differentiating environmentally friendly from degrading types of management within the combination of technologies used to produce all the items included in the consumption baskets accounted (Costanza, 2000; Fiala, 2008).

Proponents argue instead that EF is a good indicator of how the Earth's biocapacity is captured (Nathaniel and Khan, 2020; Ulucak and Khan, 2020) and distributed among end consumers in different countries or cities of the world that contribute differently to global overshooting of planetary boundaries (Rees, 2000; Wackernagel and Silverstein, 2000; White, 2007; Borucke et al., 2013; Shahzad et al., 2021). This distributional approach to the unequal access to Earth's biocapacity makes EF particularly revealing when combined with Human Development Index (HDI) values, leading to an interesting graph included in the annual reports of the Global Footprint Network (Moran et al., 2008; see also https://www.footprintnetwork.org/). To this, other social distribution indicators at regional and national level are shown by broking down EFs and their components by levels of income (Teixidó-Figueras and Duro, 2014; 2015). Accordingly, even if the EF accounting methods prevent using them as an appropriate indicator of environmental impacts, they are still useful as a distributive appraisal of the global biocapacity (Ulucak and Khan, 2020).

Many limitations or ambiguities arising from the use of global averages to account for EF have been successfully addressed by resorting to multi-regional input–output analysis (MRIO) (Hubacek and Giljum, 2003; Ferng, 2007, 2009; Wiedmann et al., 2006; 2006b; 2018b;; Wiedmann and Lenzen, 2007; Turner et al., 2007; Wiedmann, 2009; Ewing et al., 2012; Galli et al., 2013; Duro and Teixidó-Figueras, 2013; Weinzettel et al., 2014; Lin et al., 2018a). The MRIO accountancy has opened the way to connect global EF with a bottom-up accounting of the local hectares required for the provisioning of essential ecosystem services (Folke and Kautsky, 2000; Van Vuuren and Smeets, 2000; Kitzes et al., 2009), and to advance towards more robust sustainability assessments within nested open socioecological systems (Ferng, 2014; Syrovátka, 2020). Thanks to these methodological improvements, socioecological footprinting has become an integral part of the development of increasingly multidimensional ways to account for the overshoot of planetary boundaries and the evaluation of a safe and fair operating space to meet human needs (Rockström et al., 2009; Hoekstra and Wiedmann, 2014; Dearing et al., 2014; Raworth, 2017; O'Neill et al., 2018).

We adopt as starting hypotheses the two main conclusions reached by both critics and advocates of EF—i.e., that EF is not an accurate indicator of the environmental impacts which occur in the hectares accounted, but a useful indicator of the uneven distribution of the global biocapacity among nations, regions, cities, or income levels. In this article we compare EF with ELIA indicators, precisely because the latter are addressed to account for the real impacts, either negative or positive, that the material and energy flows driven by agriculture cause in the ecological functioning of landscapes. The Energy-landscape Integrated Analysis (ELIA) is another biophysically based methodology developed to set an analytical nexus between the agricultural network of socio-metabolic flows and the ensuing LUCC impacts on landscape ecology patterns and processes (Darvishi et al., 2014b; Marull et al., 2016). It has been devised to identify and give account for the energy-information interplay that take place within agroecosystems in North America and Europe from the 1830s to the 2010s (Marull et al., 2019a). ELIA indicators differentiate the best agricultural practices from the rest in terms of ecosystem services provision (Marull et al., 2020) and are currently applied in land use planning of green infrastructures (Padró et al., 2020). This allows to evaluate the feasible room for improvement and chart the best pathways to help bring humanity closer to a safe and just space for all without transgressing the global planetary boundaries (O'Neill et al., 2018). In the same vein as previous comparisons of EF with other biophysical indicators, such as HANPP (Haberl et al., 2004) and Water Footprints (Hoekstra, 2009; Galli et al., 2012), we are going to test whether ELIA modelling and indicators can overcome some of the most controversial limits that make EF a rather coarse measure of the environmental impacts of land disturbances at the landscape level (Lenzen et al., 2007). This becomes a relevant task when Ecological Economics needs to broaden and deepen the biophysical roots of the concepts and indicators used to understand and monitor the sustainability of socioecological systems (Gerber and Scheidel, 2018; Melgar-Melgar and Hall, 2020).

Both EF and ELIA have emerged out from a socio-metabolic system approach and have been devised to provide overviews of the biophysical human–nature interactions (Haberl et al, 2019; Marull et al, 2016). They also share land uses as a common ground (Haberl et al., 2004; Marull et al., 2019a), emphasizing the societal dependence upon the biological net primary production on Earth (NPP) (Jóhannesson et al., 2018). Despite these similarities, there are strong differences between EF and ELIA in their conceptualization and accounting methods of the way humans interact with their natural environments giving rise to cultural landscapes. The two indicators, EF and ELIA, have been applied to a case study in the Qazvin province, Iran, in order to compare their results and investigate whether the two methodologies bring about the same or different results when applied to this landscape scale, and how their similarities and differences deal with LUCC. To our knowledge, this is the first time this comparison has been made. The paper organizes as follows: section 2 presents a review of the backgrounds of EF and ELIA with an emphasis on a comparison of some of their main properties; section 3 considers the material and methods; section 4 focuses on the results and the discussion; and finally section 5 concludes and remarks the most important findings of the research.

2. Background and conceptual comparison between EF and ELIA

2.1. Ecological Footprint (EF)

The EF was introduced by Rees and Wackernagel in the 1990s (Rees, 1996; Wackernagel and Rees, 1996) to measure the total biologically productive area needed to meet the needs of a given human population (Wiedmann and Barrett, 2010; Nathaniel and Khan, 2020). It is expressed in global hectares (gha) with a world average biological and technological productivity for a given year (Weinzettel et al., 2014; Galli, 2015; Mancini et al., 2017; Nathaniel and Khan, 2020). Global Footprint Network (GFN) highlights that humankind needed 1.7 planets to provide ecological resources for their consumption and greenhouse gas emissions in 2018 (GFN, 2018; Zambrano-Monserrate et al., 2020), whereas it had been in 1.5 planets in 2008 (Lin et al., 2018a; 2018b;; Lee and Lin, 2019). The growing EF indicates the increasing global pressure on Earth's ecological systems.

Underpinning the EF concept of human appropriation of the bio-productive areas there lies a strong sustainability notion of the Earth's limited carrying capacity (Hoekstra, 2009; Lee, 2015; McBain et al., 2018; O'Neill et al., 2018; Ulucak and Khan, 2020). The EF aggregates the arable land (for food, feed and other agricultural products), pasture and forest (for animal grazing or timber, as well as to absorb Carbon emissions), built-up, and sea space (for fish and algae provision and to absorb CO_2) (Monfreda et al., 2004; Nathaniel and Khan, 2020; Altıntaş and Kassouri, 2020). As explained above, in this aggregation lie the main strengths and weaknesses of EF as a socioecological indicator. While it provides useful accounts for setting some of the planetary limits that should not be overshot, at the same time it prevents using it as an accurate indicator to assess how different patterns of production and consumption can help reduce current EFs.

2.2. Energy-Landscape Integrated analysis (ELIA)

The ELIA was developed by Marull et al. (2016). It relies on the theory of living systems' energy metabolism to maintain or even increase their organization (Gladyshev, 1999), and applies this to agroecosystems (Ulanowicz, 2003) by linking agricultural social metabolism with landscape complexity (Font et al. 2020). This novel methodology emphasizes the role of socio-metabolic energy throughput as an engine of the LUCC (Marull et al, 2019a), and outlines the metabolic patterns of each type or farming in a graph (see details in Supplementary Material) based on the interaction between the energy-matter flows coming from solar radiation through the photosynthesis and the labour and technical energy flows coming from society (Marull et al., 2016).

The ELIA modelling links the socio-metabolic agricultural disturbance with the ecological functioning of landscapes (Cattaneo et al., 2018). It measures the quantity of energy (E) remaining temporarily stored in agroecosystems (through the proportion of internal loops in the entire network of energy flows which allows to reproduce the landscape fund components – i.e. fertile soils and plants, livestock and farm-associated biodiversity) thanks to the information (I) embedded in the system. This I value is measured through the diversity of the network of flows with a Shannon-Wiener Index applied to the energy graph of the agroecosystem. Both indicators, E and I, bring to light how the energy-information interplay gives rise to human-transformed landscapes. ELIA does so by relating E and I indicators to the landscape (L) metrics that assess the spatial 'imprint' of the energy flows driven by farmers that change land uses and covers (LUCC), by combining the heterogeneity of landscape patterns with their ecological connectivity. All the ELIA indicators and its joint synthetic index ranges from 0 to 1 (see details in Supplementary Material).

ELIA model assumes that the interplay between E and I jointly leads to complexity, understood as a balanced level of intermediate self-organisation (Gershenson and Fernández, 2012). The cyclical nature of these matter-energy flows is relevant in order to grasp the emergent complexity and the greater information held within agroecosystems, since they imply an internal maximization of some less-dissipative fractions of societal metabolism. In the complexity carried out by these energy-material loops that maintain the agroecosystems' structure lay the foundations to better understand and develop more sustainable human-managed landscapes.

Furthermore, at the current stage it is acknowledged that the framework of a Safe and Just Space (SJS) that EF help to monitor within planetary boundaries still lacks an operational link to the social foundation of human needs provisioning (O'Neill et al., 2018). One way of deepening the analysis of these links between the human food, fibre and wood production activities, and the SJS to do so in a sustainable manner, is linking societal and ecosystem metabolisms through the Georgescu-Roegen's Fund-Flow reproductive approach (Lomas and Giampietro, 2017). This is what the ELIA cyclical-reproductive concept does to operationalize the links between different types of agricultural management, the functioning of the agroecosystem, the kind of agricultural landscape it imprints on the land, and the joint provision of ecosystem services of all sorts to society (Marull et al., 2020). By 'funds' we mean here the living structural components of agroecosystems –sometimes also called 'natural capital', such as fertile soils, livestock and farm-associated biodiversity—, which provide useful biomass flows to society provided that their own reproductive needs are met through the internal matter-energy flows that keep them alive.

2.3. EF – ELIA comparison

Table 1 compares the main features of the two methods, EF and ELIA, in terms of underlying assumptions, research question, organized complexity, system identification, and results organization.

Main underlying assumptions. EF's evaluation is based on the fundamental assumption that increasing dependence on the Earth bio-productive areas to meet human needs leads to the depletion of 'natural capital' when planetary boundaries are overshot. Therefore, long-term social welfare will diminish when humans are using of nature more than nature's regenerative potential (Haberl et al., 2004). ELIA assumes that the socio-metabolic pattern of energy flows of agro-ecosystems determines the landscape functional structure of agricultural areas (i.e. food, fibre, timber and paper EFs) and, as a result, the biodiversity-related ecosystem services they can provide beyond their own provisioning to society. Accordingly, when any increase in the provision of food, fibre, wood and paper is achieved at the expense of the landscape agroecology complexity, all the other biodiversity-related ecosystem services can be degraded (Marull et al., 2020). This sets a clear operative link between different societal production-consumption patterns and different planetary boundaries at the same time (land-system change, climate change, biogeochemical flows and biosphere integrity).

Research Question. The driving question behind EF is "How large is the bio-productive area required to support human demand?". Or, in other words, "how many hectares of land are needed to renew the resource used by a given population and absorb the Carbon emission generated?". This amount is indicated in standardized value or global hectares. The driving question behind ELIA is instead this: "How can the energy and information that flow within agroecosystems lead to complex heterogeneous landscapes with higher levels of associated biodiversity and derived ecosystem services?"

Organized Complexity. The organized complexity of EF is limited to the aggregation of different types of surfaces required to meet human consumption baskets of a human population expressed in a one-dimensional number of global hectares. The organized complexity of ELIA is multidimensional, dealing not only with the structural patterns of energy and matter flows which take place within agroecosystems according to the information driven by farmer's labour, but also with the functional dynamics of the ecological patterns and processes in the cultural landscapes 'imprinted' by these socio-metabolic flows and information.

System identification. EF builds its system identification techniques with a set of coefficients and transformations that relate end consumption baskets with the surfaces of global biocapacity required through input–output analysis (Moore et al., 2013; Jin et al., 2020). With this method, the internal dynamics of each given socioecological system that exist within the surfaces accounted remains unknown. On the contrary, for ELIA analysis system identification is in accordance with complex internal processes of agroecosystems in order to grasp the emergent complexity of landscape patterns and processes. In ELIA the cyclical nature of the matter-energy flows set in motion is fundamental in order to capture the internal dynamics that maintain the landscape structure through the energy and information held in the agroecosystem (Marull et al., 2019a).

Results organization. EF can only provide fixed goals regarding to either the supply or the demand sides, which are connected through Multi-Regional Input-Output analysis (MRIO; Wiedmann, 2009; Galli et al., 2013; Jin et al., 2020). EF global values can only be disaggregated

Table 1
Comparison of main features of the Ecological Footprint (EF) and the Energy-Landscape Integrated Analysis (ELIA).

Features	EF	ELIA
Underlying Assumption	Increasing human's dependency on bio-productive area leads to 'natural capital' depletion	Socio-metabolic energy flows driven by farmers' information determines the functional structure of agricultural landscapes
Research Question	How large is the bio productive area required to support human consumption?	How the complexity of energy and information flowing in an agroecosystem relate to landscape heterogeneity and biodiversity?
Organized Complexity	Unidimensional	Multidimensional
System Identification	Multi-Regional Input-Output Analysis (MRIO)	Complex internal processes taking place in agroecosystems
Results Organization	Goal Based	Goal Based and Process Based

into their components and correlated with other dimensions, but always taking the technical socioecological coefficients as something given. ELIA instead not only provides goals based on the overall rating of entire agroecosystems by comparing the joint indices, but also the internal indicators taking their nexuses into account. This allow differentiating environmentally friendly from degrading agricultural practices, technological options and types of management, opening a way to shift from a 'what' to a 'how' approach of sustainability assessment—i.e. to investigate those social and ecological processes that must be changed to move the agroecosystem towards more sustainable scenarios through Socioecological Integrated Analysis (SIA; Marull et al., 2020; Padró et al., 2020).

3. Material and methods

Alongside with conceptual comparisons, performing a quantitative approach facilitates a deeper contrast between different methodologies (Agostinho and Pereira, 2013). To that aim, in this research a case study in the Qazvin province (Iran), was selected to apply EF and ELIA methods and perform a statistical interpretation of the outcomes.

3.1. Case study

Qazvin province lies in northern Iran (Fig. 1) to the south of the alluvial zones of the Alborz Mountains at altitudes ranging from 250 to 4,100 m a.s.l. Based on the latest available census, it has 1,238,000 inhabitants, of whom 75% live in towns and the rest in villages (Census Centre of Iran, 2016). It contains various geomorphological regions: steep mountains to the north, more upland areas to the south and west, and plains in the centre where the average annual rainfall is just 200–300 mm. Therefore, sustaining agricultural activities in these dry farmlands, which are mixed with grazing areas, is a major challenge (Darvishi et al., 2020a). Irrigation plays a key role in agriculture and, in addition to around 22,000 deep and semi-deep wells (Regional Water

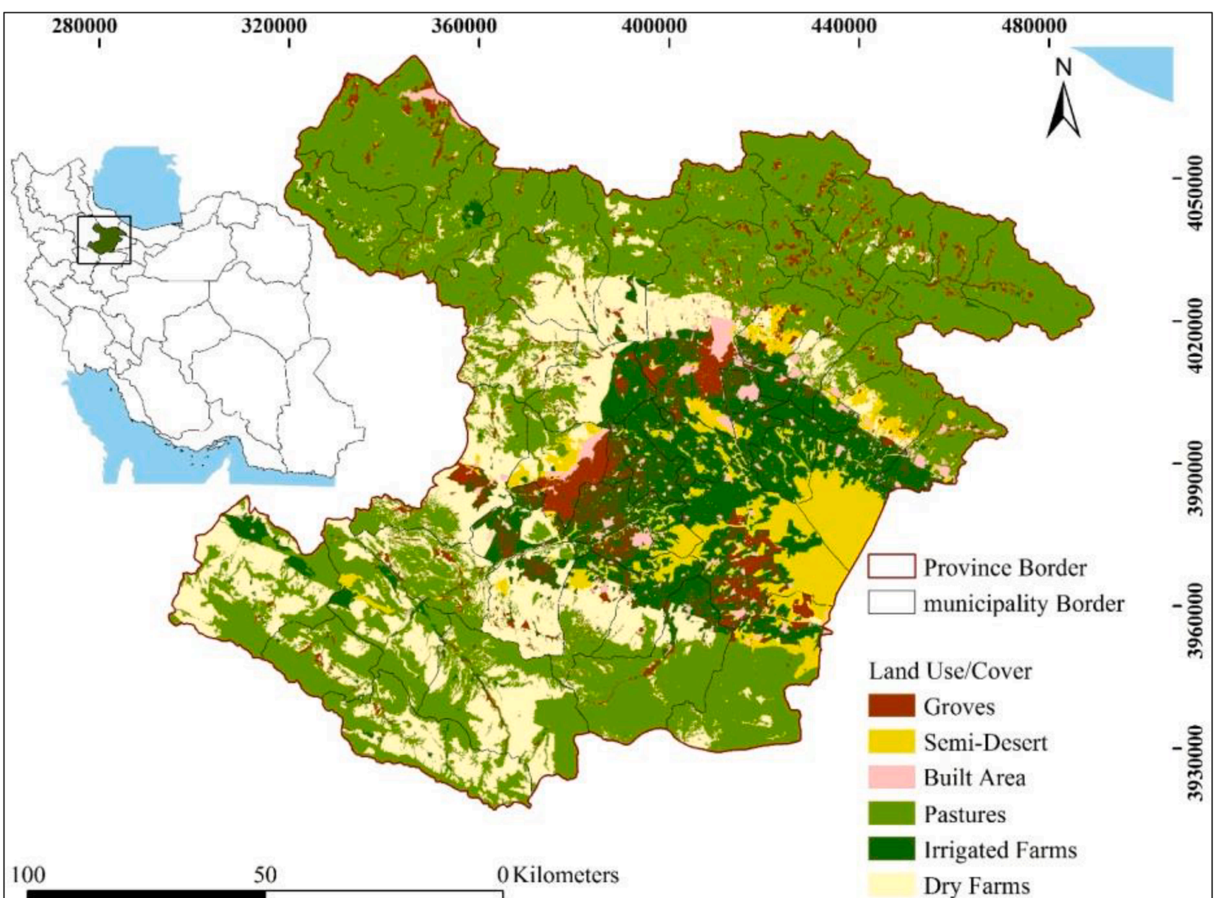

Fig. 1. Land Use/Cover Map (2018) and location of the Qazvin province (Iran). Source: Management and Planning Organization of Qazvin.

Company of Qazvin, 2008), Qazvin's agricultural lands are watered by a network of irrigation dams and channels. Geographical differences and varying precipitation rates have given rise to great variability in soil quality, which imposes different types of farm management. The crops include (in order of economic relevance) wheat, barley, alfalfa, saffron, sugar beet, lentils, beans, potatoes, watermelons, olives, pistachios, cherries, apples, peaches, apricots, walnuts, grapes, hazelnuts and hawthorns. Qazvin is one of Iran's most important agricultural centres and generates around 3% of the country's total Gross Domestic Product (GDP) (Census Centre of Iran, 2016). Another significant agricultural activity is animal husbandry, which is predominantly carried out in industrial feedlots (Yousefi et al., 2021).

The main water resource in Qazvin province is ground water, which represents 88% of water used in the agricultural sector (Regional Water Company of Qazvin, 2017). In recent years in light of the effects of climate change, the Qazvin plain has become prone to intense drought (Azizi, 2004). The 46 municipalities of the Qazvin province were studied for two principal reasons: agricultural policies are usually implemented at county level, and in Iran the county is the smallest unit for which livestock census and farming data are available (Darvishi et al., 2014a). This provides us with a good overview of the whole agrarian landscape, including farmland, pasture and natural areas, as well as livestock and societal flows.

3.2. EF method

The method used in this paper to assess the EF was the standard method developed by the Global Footprint Network (GFN, https://www.footprintnetwork.org/) (Jóhannesson et al., 2018; Lin et al., 2018b), according to the approach set forth by Wackernagel and Rees (1996, edition 2018).

Derived by natural conditions and management practices, the bioproductivity of same land uses is different between various countries around the world (Wackernagel et al., 2004). Therefore, in order to be comparable, EF is expressed in units of global hectares. For converting the areas of land into the global hectare unit, two factors are used: Equivalence Factor (EQF) and Yield Factor (YF) (Galli, 2015). EQF is a productivity-based coefficient and allows assuming, in a given year, that the primary production of a land use type is more or less than world average productivity. The standard top-down procedure applies global coefficients to make EF results internationally comparable, the bottom-up procedure uses more realistic local coefficients at a price of making the results only comparable over time in this region but not internationally: YF is calculated for the biological productivity difference between a certain land use in a region and global average in the same land use type (Kitzes et al., 2007).

EF of yearly product extraction or Carbon emissions generated is based on Eq. (1) (Lin et al., 2018a):

$$EF_P = \frac{P}{Y_c} \times EQF \times YF \tag{1}$$

where EF_P is EF associated with a product or Carbon emissions, gha; P is amount of product extracted or emission generated, t yr-1; EQFis the equivalence factor for each given LUCC type, gha Wha^{-1}; YF is the yield factor of a given land use type within a country, Wha nha^{-1}; and Y_N is the national-average yield for product extraction or Carbon absorption, t nha^{-1} yr^{-1}. The coefficients can be achieved from the GFN documents for a given year (Lin et al., 2018a).

At the first step of the estimation, the components of EF were selected. In this study the CO_2 footprint (of fossil fuel combustion and electricity); cropland footprint (embodied in crop products for society and industry as well as in feed products for livestock); grazing footprint (embodied in livestock products); and groves land footprint (embodied in orchard product) were selected regarding the availability of data. However, footprint of built-up land embodied infrastructure was not included in the calculation because of lack of reliable data. The database for calculation EF was received from different sources including reports and Qazvin Land Use Planning documents (2017) for the amount of CO_2 emitted (in Tonnes) form fossil fuels, the Management and Planning Organization of Qazvin for LUCC data, and Agriculture Ministry of Iran for agricultural and livestock censuses.

The total EF was estimated by using the sum of EF component Eq. (2):

$$EF_T = \sum_{i=1}^{4} EF_i \tag{2}$$

where EF_T is the total EF in gha, and i is the component of EF in gha.

3.3. ELIA method

ELIA outlines how agriculture is a coproduction with nature by accounting the socio-metabolic biophysical interaction between the matter-energy flows invested from outside of ecosystem and the solar radiation converted into biomass or NPP (Marull et al., 2016; Cattaneo et al., 2018). For this paper we have used the ELIA recently applied in the Qazvin province (Yousefi et al 2020). ELIA assumes that the complexity of the network pattern of energy flows is related to more heterogeneous landscapes capable to house more farm-associated biodiversity (Marull et al., 2018, 2019b). Therefore, ELIA combines the ecological landscape structure with the complexity of the interlinking pattern of energy flows, as a proxy for the landscape's material conditions to host biodiversity (Eq. (3)):

$$ELIA = \left(\frac{(E.I)L}{\max\{EI\}a}\right)^{\frac{1}{3}} \tag{3}$$

E is the energy storage in the internal cycles of agroecosystems, I is the information incorporated in the energy pattern of flows that increases its complexity, and L is the landscape functional structure. For more information about the calculation of ELIA, see Marull et al. (2019a) and the Supplementary Material.

A database was set up based on previous studies of agricultural social metabolism (Tello et al., 2015, 2016), agricultural and livestock censuses (Agriculture Ministry of Iran), and land-use data (Management and Planning Organization of Iran) as a tool for calculating a socioecological biophysical balance. Data on material flows were converted to gross calorific value in Gigajoules per hectare (Gj/ha) using the standard energy coefficients of Guzmán et al. (2014) and were used to calculate energy flows in each municipality of the province.

3.4. Cluster analysis

In order to facilitate EF and ELIA comparison a cluster analysis was performed. Cluster analysis provides the opportunity to explore results and interpretations, an expressive background for comparing methodologies (Legendre and Legendre, 1998). The 46 municipalities were grouped according to the values of the two methods (EF and ELIA) by K-means cluster analysis (IBM SPSS Statistics Version 19.0.0.329), which is based on MacQueen's algorithm (Johnson and Wichern, 2007). Heretofore, the results were standardized using z-score standardization. The appropriate number of clusters was determined by the meaningfulness of different clustering outputs interpretation with the support of variance ratio criterion (Milligan and Cooper, 1988).

3.5. Correlation between LUCC and EF – ELIA

The two methods would reveal similar or different results. Hence, we consider how their similarities and differences deal with the LUCC at spatial level. For this propose the standard values of the two methods in each municipality were subtracted, and then the average value of each cluster was calculated. After that, the correlation of difference between the two methods and landscape heterogeneity was considered.

Landscape heterogeneity (L) (Eq. (4)) is a land metric that capture landscape patterns according to the Shannon-Wiener index. The land cover types in the case study include irrigated farming, dry farming, semi desert, groves, forest, water surface, high-density pasture, medium-density pasture, low-density pasture, and unproductive area.

$$L = -\sum_{i=1}^{K} p_i \log_{k+1} p_i \tag{4}$$

where k is the number of land cover in each municipality, and p_i is the proportion of land covers i into every unit of analysis.

4. Results and discussion

4.1. Conceptual comparison

The conceptual comparison showed that albeit EF and ELIA start from similar biophysical approaches, they have followed different perspectives and methodologies of social and ecological accounting, and therefore, they offer different insights into the sustainability problem solving.

EF is measured from an 'ecocentric' perspective (Chen and Chen, 2006) relating end consumption baskets of human populations with the land biocapacities needed to provide them. The technical options and types of management adopted to use these land resources are always taken as given when using the existing average values. EF is accounted for three functions of the ecosystems used by humans—resource supply, absorption of Carbon emissions, and space occupied for infrastructure (Haberl et al., 2004). This is adequate to assess the uneven final distribution of these land resources among different human populations, but not to consider how different types of resource use and technological options can change the coefficients that convert each component of the final consumption baskets into hectares of global land.

ELIA is measured from a social metabolism perspective that takes into account the biophysical transformations and spatial distribution of matter-energy flows that actually take place in those lands used to provide food, fibre and timber to human society, considering how each pattern of biophysical flows change according to the ways through which these land resources are managed by farmers, as well as the types of landscapes generated by each type of coproduction with nature, the biodiversity maintained, and the provision ecosystem services of all kinds. To that aim ELIA depicts the dynamics of biophysical fund-flow patterns of agroecological systems in an explicit and operational manner (mathematically), in terms of the energy flows that loop through the three mains internal agroecological subsystems (nature, cropland and livestock). Although this metabolic energy analysis is limited to agroecosystems, it can distinguish how diverse types of resource use will led to different environmental impacts and provide different ecosystem services. In addition to providing a snapshot of 'what' the impacts are, ELIA can also help discover feasible and desirable ways of 'how' to reduce them to a safe and fair environmental space for all humans on Earth.

4.2. Methodological comparison

4.2.1. Result of applied methods

Fig. 2a shows the map of the EF values per hectare for each municipality. The municipalities coloured in red, demonstrate high levels of EF located predominantly in the centre of the case study. This warns that the agroecosystems of these areas are in an unsustainable development situation (Ferng, 2005), according to the excessive environmental pressure exerted by the given production and consumption patterns of the local population. Nevertheless, this EF assessment is not giving any clue on how that high level of EF could be reduced, neither to the amount of reduction required to assure natural resource sustainability at this specific landscape level (Peng et al., 2019). The high value of EF is related to the agricultural LUCC carried out in these municipalities that are predominantly groves, horticulture and agriculture.

The municipalities located in the northwest, northeast and southwest of the case study are coloured in green, showing low levels of EF. This highlights a more balanced situation between supply (local biocapacities) and demand (population and production-consumption levels), where the ecological resources of each municipality can meet the local population needs (Liu et al., 2011). This is due to the relatively low density of population and economic development in these areas, together with a lower level of consumption of fossil fuels (Wackernagel et al., 2004).

Fig. 2 b shows the ELIA value applied to the same municipalities. High values of ELIA appear coloured in read in the north, northeast, northwest, and southeast of the case study. These imply more equilibrium in the matter-energy flows that circulate within the agroecology subsystems, meaning more fund-flow complexity and integration that give rise to a more heterogeneous landscape, as well as low systemic entropy that also involves less waste and Carbon emissions. Low values of ELIA were seen in the central and southwest municipalities, and can

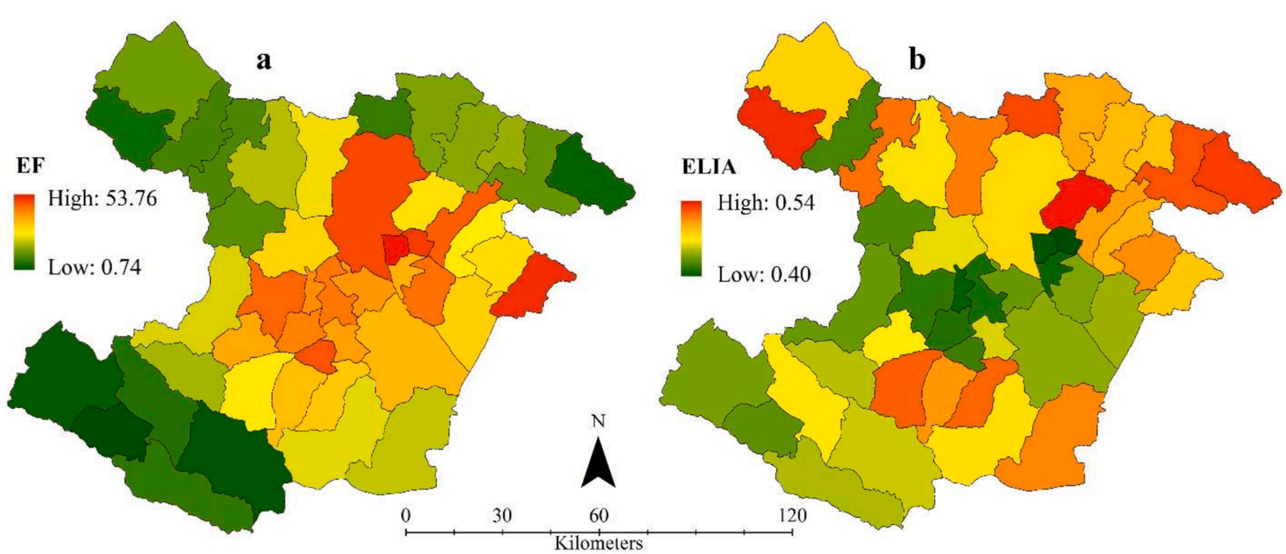

Fig. 2. Application of the Ecological Footprint (EF; a) and the Energy-Landscape Integrated Analysis (ELIA; b) to the 46 municipalities of the Qazvin province.

be attributed to the predominance of industrial agriculture, meaning a weak distribution and reinvestment of matter-energy through the land matrix in more simplified landscapes (Marull et al., 2019a). The dominated land uses in those areas are intensive irrigated agriculture that led to higher socioeconomic development.

4.2.2. Cluster analysis

The optimum cluster output appeared to be four clusters, which were characterized by the behaviour of EF and ELIA in the 46 municipalities of the sample. There is strong conflict in the results of ELIA and EF in clusters 1 and 2, where both methods obtain opposite values, while in clusters 3 and 4 there is consensus on the results obtained. This happens when the value of EF is high and the value of ELIA is low, and vice versa. Fig. 3 shows the cluster analysis results taking into account ELIA and EF. This figure represents the mean of each municipality's standardized value for the two methods in each cluster and addresses the properties of the representative case for each cluster.

Cluster 1. Both values for EF and ELIA in this cluster were lower than average. Accordingly, the first conflict between the result of EF and ELIA appear in this cluster. The lower value of EF implies higher development potential due to less impact of human on nature (Wackernagel and Rees, 1998). However, the lower value of ELIA in this cluster indicates a weaker distribution of energy cycles across the land, which means less capability for the territory to support human development biophysically, due to the reduction in the complexity of the interlinking pattern of energy carriers and the ensuing lack of landscape heterogeneity.

The LUCC of this group of municipalities are predominantly low-density pastures and dry farming, which are known for low production efficiency in Qazvin.

Cluster 2. The second cluster is characterized by having higher than average values for the two approaches. High EF values show that the end production-consumption patterns in the municipalities of this cluster requires an appropriation of natural resources larger than the ones supplied by its local environment, driving them towards a situation of ecological deficit (Hong et al., 2007). Quite the contrary, the high values of ELIA found there imply that the cropland, forestry and livestock subsystems are nearer to fund-flow equilibrium due to important role of renewable biomass reuses that reproduce the agroecosystem funds and increase its metabolic network complexity and energy storage capacity (Marull et al., 2019a). This second disagreement between EF and ELIA indicators is particularly striking.

Cluster 3. In the third cluster the value of EF is high, meaning that these municipalities are moving away from sustainable development (Moran et al., 2008) because their own bio-productive land cannot support the local population at their current consumption rates (Nakajima and Ortega, 2016). Therefore, this assessment indicates to policy makers to adopt a more restrictive strategy to protect their natural resources (Ghita et al., 2018). Along with this interpretation, ELIA reveals decreasing trends, meaning a similar diagnosis than EF but this way assessed by the lower complexity of the energy fund-flow pattern in the agroecosystem due to the high dependence on fossil fuels consumption, which has created a very simplified landscape with low land cover heterogeneity. This area includes the more developed region, with a high level of industrial production and intensified agriculture.

Cluster 4. The municipalities of the fourth cluster display low EF and high ELIA values, meaning that in this case the two methods give rise to very similar features. EF appreciates in these municipalities a significant potential to move towards regional economic development because the local biocapacity can still support the current consumption pattern and Carbon emissions of the inhabitants (Nakajima and Ortega, 2016). In turn, ELIA assessment implies that the agricultural metabolic pattern of this cluster is still well balanced and complex, based on interlinking and circulating internal matter-energy inputs that generate heterogeneous landscapes. This cluster comprises the municipalities with traditional farming and pastures scattered in the north of the case study.

4.2.3. Correlation analysis

Fig. 4 shows the correlations between landscape heterogeneity (L) and difference values between EF and ELIA. Therefore, when the values obtained of the subtraction approached to zero, the difference between the ELIA and EF results tended to decrease or disappear, and vice versa. As can be seen, where L values decrease and the landscape is simplified (cluster 3 and 4), the disagreement between the results of the two methods also tend to decrease or show quite similar results. Conversely, wherever the landscape structure is more diverse and complex (cluster 1 and 2) the two methods have shown very different results that are in conflict. High values of EF indicate more human colonization of nature while, on the contrary, high values of ELIA reveals that the energy flows are moved by farmers through their agroecosystems in a quite well-balanced manner across heterogeneous landscapes.

The explanation points out to the role of landscape heterogeneity on measuring ELIA and its absence in the EF assessment. According to Moran et al. (2008), EF is a function of three factors: resource intensity in the production of goods and services; consumption of goods and services per person; and population size. There is no relationship

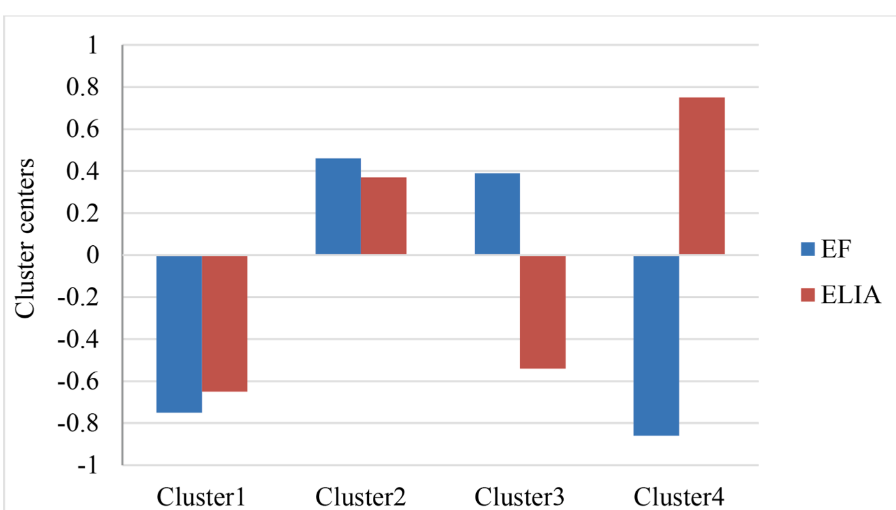

Fig. 3. Cluster centres' values of the Ecological Footprint (EF) and the Energy-Landscape Integrated Analysis (ELIA). The clusters include all 46 municipalizes of the Qazvin province.

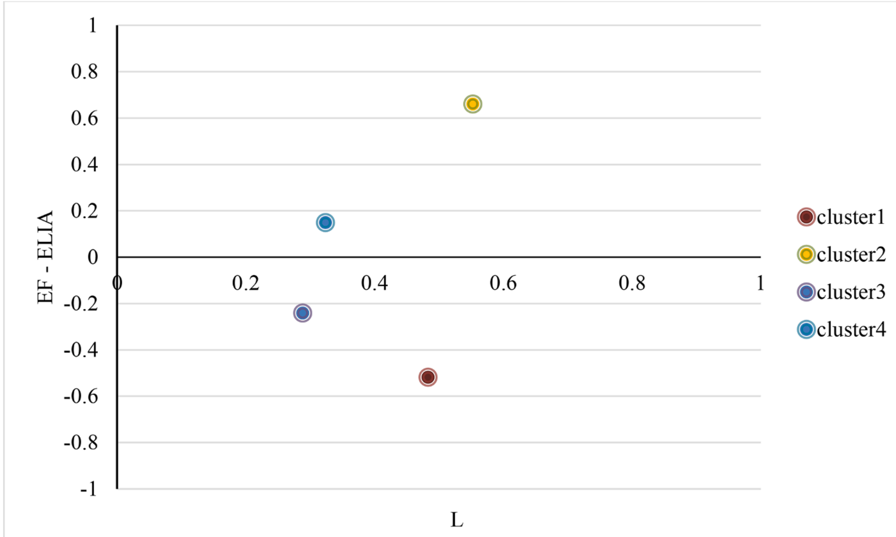

Fig. 4. Relation between the landscape heterogeneity (L) and the difference between the Ecological Footprint and the Energy-Landscape Integrated Analysis (EF – ELIA). The overall correlation between all 46 municipalizes of the Qazvin province was significant at 0.05 level.

between the patterns of landscape heterogeneity and EF calculation. In contrast, ELIA assessment links the agroecological energy flow accounting to landscape heterogeneity, which allows to differentiate environmentally friendly from degrading uses of the same amounts of land.

5. Conclusion

This research has revealed significant methodological differences between EF and ELIA, which come from the way they conceptualize human-nature relationships. By applying the two methods in the same spatial scale, this research has also tested the robustness and meaning of the concordant and discordant results obtained. These conceptual, methodological and empirical results will help researchers to choose and better use these sustainability indicators according to the problem under study.

The most important empirical difference was obtained on the correlation between the two methods and landscape heterogeneity. The EF and ELIA results only overlap when the structure of landscape is simplified. This confirms that EF is mainly a distributive indicator of the unequal appropriation of the Earth's global biocapacity by different population, but it does so ignoring how the complexity of the matter-energy flows driven by land producers can give rise to very different landscape patterns and ecological processes. ELIA is based on that nexus approach between resource use and socioecological outcomes, but its scope is limited to assess agricultural land at the landscape level.

In this EF-ELIA comparison a clear trade-off appears between the simplicity and complexity of the indicators and indices used to monitor sustainability scenarios. Simplicity has made EF a popular indicator used around the world, but at a price of making it useless to move from the 'what' to the 'how' question on desirable and viable pathways to more sustainable scenarios (de Alvarenga et al., 2012; Fiala, 2008). These pros and cons lead us to the advice raised by Ostrom (2009): "we must learn how to dissect and harness complexity, rather than eliminate it from such systems". Nevertheless, from a methodological point of view, the database needed to calculate EFs is composed of a minimal group of factors that make it easy to apply, whereas ELIA requires a database much more demanding and time consuming. This turns ELIA into a better indicator not only to assess the current situation, but to help find out possible ways of improvement for decision-making processes (Marull et al., 2020; Padró et al., 2020).

The ELIA concept and methods establish a new link between Material and Energy Flow Accounting (MEFA) developed in Ecological Economics to analyse socio-ecological interactions, and Landscape Ecology metrics used to assess the LUCC impacts (Gerber and Scheidel, 2018). Underpinning both approaches, there is an acknowledgment of the biophysical basis of human wellbeing and of the unavoidable limits of the ecosystem services the society can obtain from the Earth biocapacities. This recognition implies the need for society to invest in maintaining these biophysical structures and processes in good ecological conditions, so that their own self-reproduction continues to provide these ecosystem services in the future. That interdisciplinary research combining landscape ecology with socio-metabolic approaches leads, in turn, to see human activity not only as an ecological disturbance but as part and parcel of the landscape dynamics as such. The study of LUCC is broaden from strictly physical, biological and ecological dimensions to economic, sociological and anthropological ones.

Society cannot be conceptualized as a separate part of landscapes. Seeing human activity only as an agent of ecological detrimental changes obscures many 'transactional processes' taking place in the interaction of society with landscape dynamics that are biological and cultural at the same time, and may keep or enhance landscape eco-diversity as well as degrade it. Therefore, ELIA accounting and indicators belong to those views that are broadening the conceptual and methodological scope of quantitative landscape ecology from the natural to social sciences and humanities, from strictly bioecological issues to much more complex human-ecological change, and from closed islands of nature protection to the ecological patterns and processes in the open landscape continuum of land matrices (Naveh, 2007; Zube, 1987). As in any other area of sustainability science, developing this socio-metabolic landscape research means overcoming conventional reductionist views and adopt holistic approaches of wholeness, by focusing the analysis on how some ordered complexity can actually arise (or be degraded) in agricultural landscapes. The intellectual outcome of this endeavour is to keep developing landscape agroecology as an innovative field of research (Wojtkowski, 2004; Giampietro, 2004; Gliessman, 2007; Tomich et al., 2011; González de Molina and Toledo, 2014; Guzmán and González de Molina, 2017).

CRediT authorship contribution statement

Maryam Yousefi: Conceptualization, Data curation, Formal analysis, Writing - original draft. **Asef Darvishi:** Conceptualization, Data curation, Formal analysis, Writing - original draft. **Enric Tello:**

Conceptualization, Writing - review & editing. **Shahindokht Barghjelveh:** Writing - review & editing. **Naghmeh Mobarghaee Dinan:** Writing - review & editing. **Joan Marull:** Conceptualization, Writing - review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.107439.

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