Journal of Cleaner Production 408 (2023) 137136

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Regenerative economics at the service of islands: Assessing the socio-economic metabolism of Samothraki in Greece

Filippos K. Zisopoulos [a,b,*], Dominik Noll [c,d], Simron J. Singh [e], Daan Schraven [b], Martin de Jong [a,f,g], Brian D. Fath [h,i,j], Sally Goerner [j], Ken Webster [k], Dan Fiscus [j], Robert E. Ulanowicz [j,l]

[a] *Rotterdam School of Management, Erasmus University Rotterdam, Rotterdam, the Netherlands*
[b] *Integral Design and Management, Department of Materials, Mechanics, Management & Design, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands*
[c] *Institute of Social Ecology, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria*
[d] *Mediterranean Institute for Agriculture, Environment and Development, University of Évora, Portugal*
[e] *School of Environment, Enterprise and Development, University of Waterloo, Waterloo, Ontario, Canada*
[f] *Erasmus School of Law, Erasmus University Rotterdam, Rotterdam, the Netherlands*
[g] *Institute for Global Public Policy, Fudan University, Shanghai, China*
[h] *Department of Biological Sciences, Towson University, Towson, United States*
[i] *Advancing Systems Analysis Program, International Institute for Applied Systems Analysis, Laxenburg, Austria*
[j] *Research Alliance for Regenerative Economics & Planetary Health Lab, Edinburgh University, Edinburgh, United Kingdom*
[k] *Department of Management and Engineering, University of Linköping, Sweden*
[l] *Department of Biology, University of Florida, Florida, United States*

A R T I C L E I N F O

Handling Editor: Patrizia Ghisellini

Keywords:
Circular economy
Ascendency analysis
Ecological network analysis
Resilience
Robustness
Island metabolism

A B S T R A C T

For many islands, the answer to the question *"why a locally, self-sustaining, and regenerative economy is needed?"* is clear. The struggle often lies in the *"how"*. Here, we argue that tools from regenerative economics, which follow an island economy-as-an-organism analogy, offer valuable and complementary insights to socio-metabolic research. Indicators from flow-based and information-based ecological network analysis can quantify properties of an island's socio-economic metabolism (SEM) which are related to cycling, resilience, and degree of mutualism, among others. To illustrate the applicability of these methods, we select Samothraki in Greece as a case study. Results show that over the years the island became very efficient in streamlining imported resources, experiencing physical growth as indicated by a substantial increase in its total material throughput. This growth was attributed to a high *degree of order* (i.e., network efficiency) endowed by the constraining (ordered) part of the linear structure of the island's SEM. The disordered part of its SEM which is related to *resilience*, played a much smaller role which became progressively more important over the years, albeit to a limited degree. While the island exhibits an increasing trend in its *robustness*, its value over the years studied was well below what is typically observed for healthy natural ecosystems, and its current SEM has a very low ability to generate internal flow activity and cycling of resources per unit input. This limited *robustness* is due to the island's dependency on imports but also due to its linear SEM which had a very small number of feedback loops in its network. A scenario analysis showed that a reticulated network structure would theoretically endow the island with increased *resilience*, and hence *robustness*, by allowing for more internal resource flow activity to be circulated as regenerative re-investment. This article highlights that methods from regenerative economics can be used as diagnostic tools to assess and monitor the impact of strategies related to circular economy interventions on network properties, and to illuminate their effect on the regenerative potential of islands.

* Corresponding author. Rotterdam School of Management, Erasmus University Rotterdam, Rotterdam, the Netherlands
E-mail address: Zisopoulos@rsm.nl (F.K. Zisopoulos).

https://doi.org/10.1016/j.jclepro.2023.137136
Received 31 October 2022; Received in revised form 6 March 2023; Accepted 6 April 2023
Available online 17 April 2023

1. Introduction

Inhabited small islands are threatened by resource challenges, waste generation, and consequences of climate change such as the increasing frequency and intensity of extreme weather events and sea level rise (Singh et al., 2020). Specific combinations of resource-use patterns and their trajectories further increase the proliferation of risk on island systems (Singh et al., 2022). The geomorphological characteristics of islands constrain the flow of materials where innovative approaches to reduce and manage the increasing amount of solid waste are urgently needed (Eckelman et al., 2014). This is unsurprising since many islands lack appropriate waste management infrastructure while suffering from over-tourism (Sciacca, 2020). Currently, a substantial amount of municipal waste generated in Small Island Developing States (SIDS) is illegally dumped or burned or ends up littering coastlines and the oceans (Elgie, 2022; Elgie et al., 2021; UNEP, 2019). Moreover, communication between multiple stakeholders can be challenging where effective solutions for one issue can manifest as trade-offs, or shift the burden they try to address, elsewhere (Singh et al., 2020). Approaching waste challenges from a socio-metabolic perspective where solid waste represents an opportunity for the use of secondary resources could be a beneficial way forward for the sustainability and resilience of islands.

Socio-metabolic research (SMR) is a scientific field which analyzes the biophysical stocks and flows associated with society's production and consumption patterns, along with their socioeconomic drivers (Haberl et al., 2019). It is parent to the concept of industrial symbiosis which engages with the question of how industrial waste materials can become useful resources for other industries, and it is mostly applied in industrial parks (Chertow, 2008; Salomone et al., 2020). SMR has, therefore, the potential to consider flows of all sectors of an economy, their interaction, and trade-offs in a holistic manner to derive recommendations for more sustainable resource use and to help in understanding better the resilience aspects of a circular economy (CE) in islands (Mayer et al., 2019).

The CE is an economic model which promises to alter production and consumption patterns by reducing waste and pollution, by keeping products and materials in use for as long as possible, thus minimizing the need for new inputs, and by regenerating nature (Ellen MacArthur Foundation, 2019). Currently, it is being explored for its potential by various islands. For example, African island states could benefit by a transition to a CE not just for addressing holistically waste generation and stock management, but also for developing regenerative ocean-based activities, for creating jobs, and for facilitating knowledge exchange between islands (Andriamahefazafy et al., 2022). A study at the Orkney Islands showed that the carbon footprint of the local community could be reduced substantially by diverting waste streams which would otherwise be shipped to the Shetland islands, towards an anaerobic digestion plant which is inclusive of the waste disposal system for combined heat and power generation to serve *"97% of energy needs for the largest distillery on the island, 4 compressed natural gas trucks for the island or a 1-acre greenhouse"* (Reynolds et al., 2022). An indicative yet not exhaustive list of other island cases where the CE has been explored include Guam (Schumann, 2020), Mauritius (Kowlesser, 2020), and the Åland islands (Kiviranta et al., 2020). Given the increasing interest in this field, it is pertinent that rigorous quantitative network-based methods and indicators are adopted to study not only how to grow but also how to develop socio-economic systems.

It is well established that biomimetic principles and network-based methods can be used for studying human systems as complex adaptive systems (Chatterjee et al., 2022; de Jonge and Schückel, 2021; de Souza et al., 2019; Reap and Layton, 2017; Scharler et al., 2018; Scharler and Borrett, 2021) and for developing them by learning from nature's CE (Tate et al., 2019). Expecting the regenerative potential of an economy to increase with increasing circularity rates of resources, we argue that any transition pathway towards a CE would benefit from an assessment of a socio-economic system's potential for regeneration by studying the network properties of its socio-economic metabolism. For this purpose, we define a regenerative economy as a socio-economic system which aims to drive inclusive prosperity while addressing societal needs within planetary boundaries by continuously channeling money, information, and renewable natural resources into self-feeding, self-organizing, and adaptive learning internal circular processes which nourish its capacity to thrive for long periods of time (Research Alliance for Regenerative Economics, 2022). This definition is largely based on findings of ecosystem ecologists who used network-based tools and information theory to study healthy natural ecosystems. They theorized that healthy ecosystems tend to have network structures which balance within a relatively narrow range of around 60% redundancy in their connections for enhanced resilience and a corresponding 40% efficiency in streamlining resources through their system; a range which endows the system with robustness and has been termed as the *"window of vitality"* (Ulanowicz, 2009; Ulanowicz et al., 2009; Zorach and Ulanowicz, 2003). Yet, they also left open the possibility of *"other types of sustainable systems"* to balance around a different ratio (Ulanowicz, 2020). In essence, this eco-mimicry approach follows a normative ideal and requires further research (Kharrazi et al., 2013).

To this end, we apply two network analysis methods: ascendency analysis which stems from information theory, and ecological network analysis which is based on thermodynamics. These two methods are chosen because they offer indicators which capture the following five principles from regenerative economics (RE): 1) cross-scale circulation of resources (for long term sustainable operation of the system via the mutual support of its interlinked components), 2) regenerative reinvestments (for building, maintaining, and repairing the internal capacities of a system), 3) balance of resilience and efficiency (for systemic health as observed in natural ecosystems), 4) sufficient number and diversity of roles (for proper system functioning), and 5) degree of mutualism (for increased robustness due to mutualistic relations between system components). The interested reader can find more information about these principles in the work of Fath et al. (2019a,b). Examples where these methods have been applied to assess the resilience of human networks include studies on water distribution networks in eco-industrial parks (Dave and Layton, 2020), on the reliability and survivability of power systems (Huang et al., 2022), on large networked architectures of *"systems of systems"* (Chatterjee et al., 2021a, b), on global commodity trade networks (Kharrazi et al., 2017), and on economic networks (Iskrzyński et al., 2021).

We select Samothraki island in Greece as a case study for two reasons. Firstly, because it is the only island for which a comprehensive mass-balance study using SMR was conducted and for which a relevant metabolic database in the form of a time-series exists in published form (Noll et al., 2022). Secondly, because the island's economy remained largely based on the domestic extraction of biomass despite its growing dependence on imports over the years (Noll et al., 2022). This implies that, at least theoretically, the island has the potential to become once more a circular economy if it manages to shift from non-renewable imports to domestically extracted renewable resources under consideration that local consumption rates do not surpass the regeneration of those renewable resources.

Ultimately, this research aims to illuminate which additional insights regarding sustainability transitions of socio-economic systems can be drawn from RE which cannot otherwise be provided by SMR. To organize the study, we formulate two research questions.

1. How did the regenerative potential of Samothraki (as captured by indicators from RE) evolve between 1929 and 2019?
2. How would the regenerative potential of Samothraki develop theoretically if substantial circularity measures would be implemented?

Section 2 describes the methodology, provides context about the socio-economic metabolism of Samothraki and about the scenarios assessed. Sections 3 and 4 discuss the results after analyzing the revised time series data of Samothraki's socio-economic metabolism by Noll et al. (2022). Finally, Section 5 presents the conclusions.

2. Methods

We assess the socio-economic metabolism of the island of Samothraki by examining the network properties of its Sankey diagram whereby the flowing medium through the various processes (nodes of the network) is its material flow (time series data) between 1929 and 2019 as reported by Noll et al. (2022). Then, we apply two network-based methods ascendency analysis and ecological network analysis to quantify various indicators to capture five of the principles of regenerative economics as described by Fath et al. (2019a,b).

2.1. Ascendency analysis

Here, we present a summary of the main methodological aspects of ascendency analysis and the interested reader is referred to the work of Robert Ulanowicz (2002, 2009, 2020). The data of the network are encoded into a matrix as elements to conduct the following calculations where a material flow from node i to node j is symbolized with T_{ij} (Gt/year). The total system throughput $T_{..}$ (Gt/year) is:

$$T_{..} = \sum_{j=1}^{n} z_j + \sum_{j=1}^{n}\sum_{j=1}^{n} T_{ij} + \sum_{i=1}^{n} y_i \tag{1}$$

The total internal flow system throughput TST_{flow} (Gt/year) is:

$$TST_{flow} = \sum_{j=1}^{n}\sum_{j=1}^{n} T_{ij} \tag{2}$$

The capacity of the network for development H (bits) is:

$$H = -\sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)\log_2\left(\frac{T_{ij}}{T_{..}}\right) \tag{3}$$

The average mutual information of the network X (bits) is:

$$X = \sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)\log_2\left(\frac{T_{ij}}{T_{i.}}\frac{T_{..}}{T_{.j}}\right) \tag{4}$$

Here, $T_{i.}$ represents the sum of flows that are leaving node i whereas $T_{.j}$ represents the sum of flows that are entering node j during the same period (Ulanowicz et al., 2009). Assuming that the network is at steady state, the sum of nodal inflows and of nodal outflows are equal: $T_{i.} = T_{.j} = T_i$ (Fath, 2012).

The redundancy or resilience of the network H_c (bits) is:

$$H_c = -\sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)\log_2\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right) \tag{5}$$

The capacity of the network to develop H is the sum of its ordered and disordered parts:

$$H = X + H_C \tag{6}$$

By scaling these three properties with $T_{..}$ the units become Gt bits/year. Then we can calculate the ascendency A, the overhead Φ, and the total (scaled) capacity of the network to develop C:

$$A = T_{..}X \tag{7}$$

$$\Phi = T_{..}H_c \tag{8}$$

$$C = A + \Phi \tag{9}$$

The degree of order of the network is:

$$a = \frac{X}{H} \tag{10}$$

The robustness of the network R is

$$R = -\alpha\ln(\alpha) \tag{11}$$

To construct the robustness curve, the degree of order is plotted against the robustness. In this way, it is possible to identify whether the network under study is more brittle, more redundant, or whether it is near or within the *"window of vitality"* (Appendix C).

The number of roles n, here, describes the number of processes (i.e., nodes in the abstracted network) which are used to characterize the socio-economic metabolism of human systems, and is:

$$n = 2^X \tag{12}$$

The number of links per node c, here, describes the number of links per socio-economic process, is:

$$c = 2^{\left(\frac{H_c}{2}\right)} \tag{13}$$

2.2. Ecological network analysis

In this section, we present a summary of the main methodological aspects of ecological network analysis. The interested reader is referred to the following publications (Fath, 2018; Fath et al., 2007; Fath and Scharler, 2018). The elements of the original data matrix which represent the directly measurable flows (or probabilities of flow) between two nodes i and j, are normalized in an output driven way ($g_{ij,output}$), but they can also be calculated in an input driven way ($g_{ij,input}$):

$$g_{ij,output} = \frac{T_{ij}}{T_{i.}}\ or\ g_{ij,input} = \frac{T_{ij}}{T_{.j}} \tag{14}$$

A matrix G is created which is known as the direct flow intensity matrix:

$$G = (g_{ij}) \tag{15}$$

To calculate the indirect flows in the network, matrix G is raised to n powers and the produced matrixes are summed up. The newly formed matrix is called the integral flow matrix N with elements n_{ij}:

$$N = (n_{ij}) = G^0 + G^1 + G^2 + \dots G^n = (I - G)^{-1} \tag{16}$$

The elements of each of these n matrixes represent the probability of the flows to reach other nodes in the network in n steps. The indicator DI shows whether there is dominance of indirect effects:

$$DI = \frac{\sum_{i,j=1}^{n}(n_{ij} - g_{ij} - \delta_{ij})}{\sum_{i,j=1}^{n} g_{ij}} \tag{17}$$

where δ_{ij} is a binary variable taking the value of one when there is a connection between node i and node j, and zero otherwise.

The elements of the original dataset are normalized once more with the compartmental throughflow $T_.$ but this time by considering the difference of mutual flows between two nodes to construct the direct utility flow matrix D:

$$D = (d_{ij}) \tag{18}$$

$$d_{ij} = \frac{T_{ij} - T_{ji}}{T_i} \tag{19}$$

Following a similar procedure, this matrix is raised to n powers, and the produced matrices are summed up to create an integral matrix U with elements u_{ij}:

$$U = (u_{ij}) = D^0 + D^1 + D^2 + \dots D^n = (I - D)^{-1} \tag{20}$$

This matrix can be used to construct other matrices the elements of which are signs (rather than numerical values) and which indicate whether a relation is directed from node *i* to node *j* or vice versa. There are four different combinations of signs which describe the different types of relationships between the nodes: mutualistic (+,+), exploitative (+,−), exploited (−,+), and competitive (−,−). These matrices are used to calculate the degree of mutualism *M* and degree of synergism *S*:

$$M = \frac{S_+}{S_-} = \frac{\sum max\left[sgn\left(u_{ij}\right), 0\right]}{-\sum min\left[sgn\left(u_{ij}\right), 0\right]} \tag{21}$$

$$S = \frac{\sum max\left(u_{ij}, 0\right)}{-\sum min\left(u_{ij}, 0\right)} \tag{22}$$

To calculate Finn's Cycling Index (*FCI*), the total system throughput for system cycling (TST_{ci}) is calculated first to capture the cycling of flows through each one of the nodes:

$$TST_{ci} = \frac{(n_{ii} - 1)}{n_{ii}} T_i \tag{23}$$

$$FCI = \frac{\sum TST_{ci}}{TST_{flow}} \tag{24}$$

The average path length (*APL*) which is also known as network aggradation, is calculated as follows:

$$APL = \frac{TST_{flow}}{\sum_{i=1}^{n} z_i} \tag{25}$$

2.3. Case study: Samothraki

Samothraki is an island of 178 km^2 located at northwest Greece with about 2,800 inhabitants throughout the year and with additional 30,000 annual visitors, mainly during mid-July to mid-August (Fischer-Kowalski et al., 2020). Of those, 22,000 are tourists and the rest seasonal workers, second-home owners, and other. This means that on an average day in the summer the island has about 4,300 people and over the whole year 3,500. The island has distinct lush vegetation on its north side, rocky plateaus on the south side, and fertile grounds on the west side with rich agricultural diversity (Fetzel et al., 2018). Over the course of 90 years, it has increased its domestic material consumption threefold, transitioning gradually from an agrarian socio-metabolic profile which was based almost exclusively on the use of renewable resources, towards an industrialized biophysical economy which is largely dependent on imports, degenerating the island's ecosystems due to severe overgrazing, overfishing, and waste generation (Noll et al., 2019, 2020; Fischer-Kowalski et al., 2020). Solid waste generation increased fivefold, accounting for almost one-half the size of material stocks in use and with the lack of waste processing facilities nearby, the island has been exporting its municipal waste (approx. 1.2 kt in 2019, half of which was composed of organic waste) to the mainland (Noll et al., 2022).

As a first step for the analysis, we abstract the socio-economic metabolism of Samothraki into an interconnected network of nodes (Fig. 1). Here we note that the main feedback loop of the network is socio-economic cycling which *"could only be ascertained for road construction activities in which some shares of the output materials are being reused for new roads or maintenance works"* (Noll et al., 2022). Socio-economic cycling is calculated by using a model for road construction which assumes that a certain share of road maintenance is being recycled (Miatto et al., 2017; Noll et al., 2019). Then, we construct an input-output type of matrix populated with the updated data of material flows from 1929 to 2019 from Noll et al. (2022) which we analyze within the RE framework using ascendency and ecological network analyses.

2.4. Comparison of scenarios

To achieve a more sustainable social metabolism on the island, Noll et al. (2022) proposed to increase material circularity not only by focusing on the material output side but to also lower the overall scale of the biophysical economy. This could be done by reducing resource demand through a combination of lowering livestock numbers, substituting fossil fuel use, improving the utilization of locally available renewable and secondary resources, and replacing problematic imported materials (Noll et al., 2019, 2022). With these aims in mind, we compare the island's metabolism of 2019 with alternative scenarios which, on a more abstract theoretical level, intend to capture the impact of implementing measures and practices based on waste hierarchy

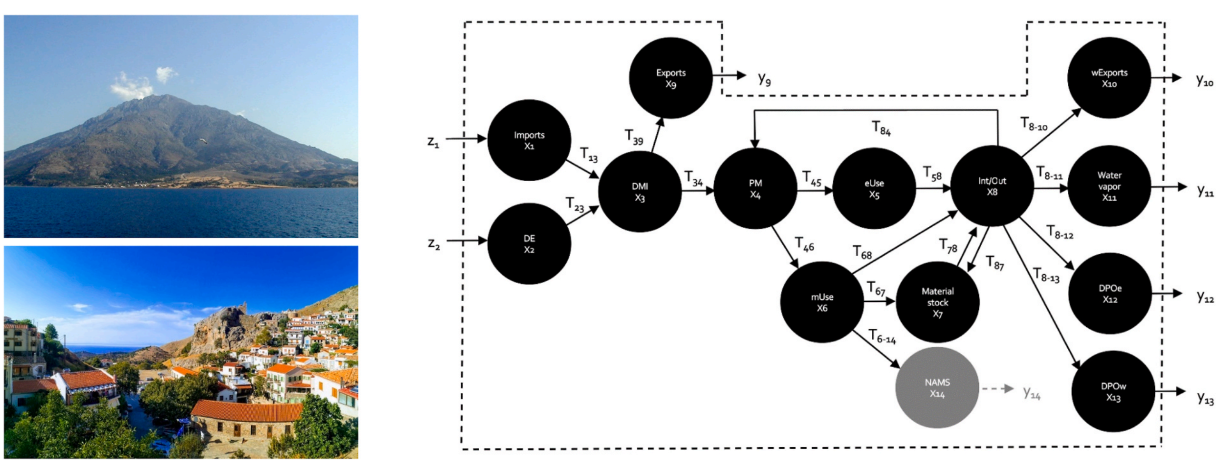

Fig. 1. *Left:* Island of Samothraki, and the view from Chora, the capital of Samothraki (upper picture from Wikipedia, lower picture by Marianna Stylianou on Unsplash). A more detailed map of the island is shown on Appendix A. *Right:* Network of Samothraki abstracted from the socio-economic metabolism depicted in the Sankey diagrams of Noll et al. (2022) where z_i and y_i are boundary input flows and output flows of materials respectively, and T_{ij} are material flows from node *i* to node *j*, DE: domestic extraction, DMI: domestic material inputs, PM: processed materials, eUse: material inputs for energy use, mUse: material inputs for material use, Int/Out: Interim outflows, wExports: exported waste, DPOe: domestic processed output emissions, DPOw: domestic processed output waste, NAMS: Net addition to material stocks is treated both as a node and as an outflow (y14) for methodological reasons, because: a) ecological network analysis assumes the system to operate at steady state (Fath et al., 2019), and processes which play essential roles in a system's function, and which possess a certain level of independence, are to be modelled as nodes (Chatterjee et al., 2021a, b). Here, flow T_{87} represents the net addition to livestock and humans (given that animals also consume biomass and generate stocks and that some are consumed locally or exported). To maintain the system in steady state for conducting the analysis, this flow has been assumed to move from the node of interim outputs towards the node NAMS. All flows have units kt/year.

principles on the regenerative potential of the island.

- Scenario 1 examines the case of implementing the four proposed measures by Noll et al. (2022) which include: a) the reduction of grazing by 50% through reduction of the population of small ruminants, b) the reduction of fuel wood extraction by 20%, c) the replacement of 1.2 kt/year of imported construction materials with wood ash and/or straw, and d) the replacement of 75 t/year of imported insulation materials and other construction materials with sheep wool. The authors estimated that these four measures could theoretically reduce the domestic material consumption (DMC) by −21.1%, −3.7%, −2.5%, and −0.1%, respectively, leading to an overall reduction in DMC of approximately −27.4% or −13 kt/year. They could also reduce the domestic processed output (DPO) by −27.8%, −3.1%, 0.0%, and −0.1%, respectively, leading to an overall reduction in DPO (both waste and emissions) of approximately −31% or −11 kt/year. Here, these percentages are considered by adjusting the sizes of all the material flows to which they correspond. The calculations are based on the equations shown inAppendix B.
- Scenario 2 examines the case of abolishing fossil fuels in addition to the measures of scenario 1. This assumes a complete yet theoretically feasible transformation of the local transport sector and the establishment of a local renewable energy network (e.g., of photovoltaic) and a small number of sea-based wind turbines. In this case, the deep-sea cable could be used to balance supply and demand with the mainland grid. Another example could be the *"substitution of conventional scooters for tourists with electric ones, in combination with the establishment of some solar powered loading stations, in collaboration with local businesses"* (Noll et al., 2022). It is also assumed that oil heating systems are not used anymore under the condition that these would not be substituted by local biomass.
- Scenario 3 examines how the network properties could be affected in the theoretical case of a more interlinked socio-economic metabolism which is advanced in terms of circular economy. In addition to the measures of scenario 1 and 2 which reduce the size of several flows (i.e., imports of 10 kt/year, DE of 30 kt/year, and output flows such as waste and emissions to be reduced substantially compared to 2019), some of the socio-metabolic processes are assumed to be interconnected to a larger degree with each other. This assumption is meant to capture the adoption of more sustainable production and consumption patterns through the implementation of a variety of circularity measures by the local society (both the private and the public sector) and the recirculation of waste back in the metabolism as resources. However, this is considered in an aggregate and arbitrary manner whereby the local society is assumed to be able to overcome barriers related to new technologies and investments which impede more sustainable material use. These interventions shown in Fig. 2 are assumed to influence mainly the interlinkages between nodes X4 (PM), X6 (mUse), X7 (Material Stock), X8 (Int/Out), and X9 (Exports). Such measures are assumed to be applicable mainly to non-renewable materials because biomass as such (which on Samothraki consists of food, feed, and firewood) is considered circular, but only if it is consumed at the same rate as it is grown.

3. Results

3.1. Results from ascendency analysis

The results of both ascendency analysis and ecological network analysis are summarized in Table 1. Ascendency analysis showed that over the past 90 years Samothraki reduced its *degree of order* by 13% and increased its *robustness* by 75%. Both indicators stabilized during the recent two decades around the values of 0.75 and 0.21, respectively (Fig. 3a). As stated above in the methods, the total system *capacity* can be partitioned into the efficient and redundant network functions, referred to here as ordered and disordered, respectively. The increased *robustness* was the result of an overall increase both in the ordered part (*ascendency*) of the island's metabolism by 221% as well as in the disordered part (*overhead*) by 597% (Table 1 and Fig. 3b). These two properties led to an overall increase by 270% in the total *capacity of the island for development* where the contribution of *ascendency* was much larger than the *overhead*, but which decreased substantially from 87% in 1929 to 75% in 2019 (Fig. 3c). This implies that over the years the disordered part of the socio-economic metabolism's network started to play a more important role on the *resilience* of island albeit to a limited degree.

The network property *ascendency* can be further disaggregated down to its two components: the *average mutual information* and the *total system throughput*. The former component is an intensive property which captures the qualitative development of the island's socio-economic metabolic network which, over these 90 years and on average, played a minor role, accounting only for about 5–6% of *ascendency* (data not shown). The latter component is an extensive property which captures growth quantitatively in terms of total material flow activity, and it was the main contributor of *ascendency*, accounting for the rest 94–95% (data not shown). The large share of the *total system throughput* is in line with the expansion of the material stock and its maintenance requirements,

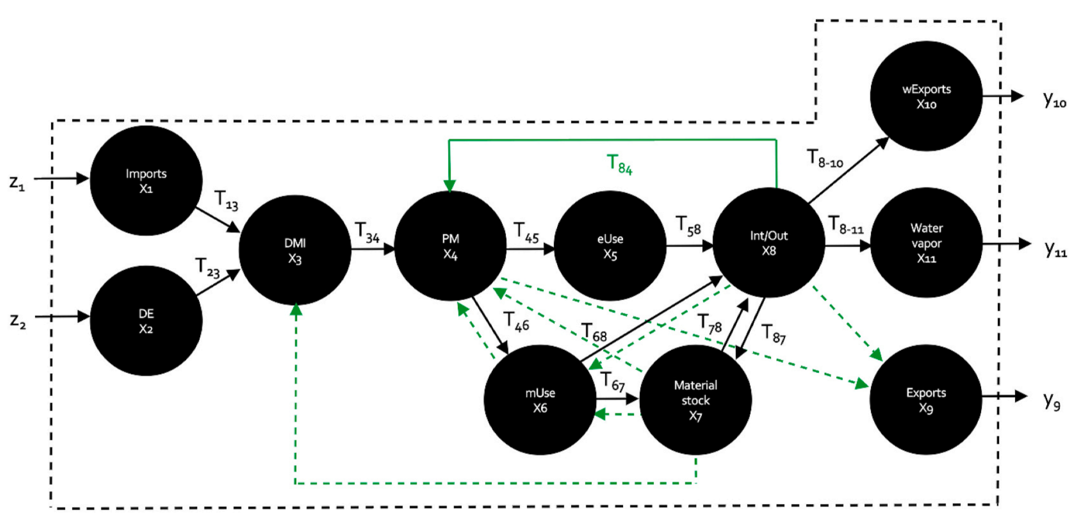

Fig. 2. Scenario 3 depicting with green the added or otherwise affected material flows. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Results from ascendency analysis (AA) and from ecological network analysis (ENA) which are relate to the five studied principles of regenerative economics from Fath et al. (2019a,b) whereby only the end points of the time series between 1929 and 2019 are shown per indicator, along with their relative changes, and minimum and maximum values.

Principle	Method	Indicator	Symbol	Units	1929	2019	$\Delta_{2019\text{-}1929}$	min	Year	max	Year
Cross-scale circulation	Both	Boundary inputs	Σz_i	kt/year	17	56	222%	17	1931	235	1990
	Both	Total system throughput	TST.	kt/year	119	386	224%	114	1931	1456	1990
	Both	Total system throughput (internal)	TST_{flow}	kt/year	84	273	225%	81	1931	985	1990
	Both	Average path length	APL	–	4.8	4.9	1%	4.2	1990	5.0	1975
Regenerative re-investments	ENA	Finn cycling index	$FCI_{2019\text{-}1967}$	%	0.01%	1.28%	0.80%	0.00%	1961	1.85%	1996
Balance between efficiency & resilience	AA	Average mutual information or efficiency	X	bits	2.1	2.1	−1%	1.9	1990	2.1	1959
	AA	Overhead or redundancy or resilience	H_c	bits	0.3	0.7	115%	0.3	1938	0.7	2011
	AA	Capacity to develop	H	bits	2.4	2.8	14%	2.3	1990	2.8	2011
	AA	Ascendency or efficiency	A	kt bits/year	249	799	221%	237	1931	2831	1990
	AA	Overhead or redundancy or resilience	Φ	kt bits/year	38	264	597%	35	1931	461	1990
	AA	Capacity to develop	C	kt bits/year	287	1063	270%	273	1931	3292	1990
	AA	Degree of order	α	–	0.868	0.751	−13%	0.746	2011	0.872	1938
	AA	Robustness	R	–	0.123	0.215	75%	0.120	1938	0.219	2011
Sufficient number & diversity of roles	AA	Number of roles	n	–	4.3	4.2	−2%	3.8	1990	4.4	1959
	AA	Number of links or link density	c	–	1.1	1.3	14%	1.1	1938	1.3	2011
Degree of mutualism	ENA	Direct flow (flow intensity matrix G)	Direct flow	–	8	8	0%	8	1931	8	2016
	ENA	Total flow (integral flow matrix N)	Total flow	–	22	25	12%	20	1970	25	2014
	ENA	Indirect flow (G-N)	Indirect flow	–	14	17	19%	12	1970	17	2014
	ENA	Degree of indirect effects	DI	–	1.78	2.12	19%	1.50	1970	2.19	2014
	ENA	Degree of indirect effects	Indirect effects	%	64%	68%	4%	60%	1970	69%	2014
	ENA	Degree of mutualism	M	–	1.281	1.000	−22%	1.000	2011	1.317	1930
	ENA	Degree of synergism	S	–	1.012	1.002	−1%	1.001	2018	1.019	1931

with the increased feed consumption by the large numbers of small ruminants, and with the increased consumption patterns of the residents and tourists (Noll et al., 2022). The peaks occurring in 1970, 1983, and 1990 (Fig. 3b and d), relate to the construction of the first large port in Kamariotissa, to the road network extension from 8.5 to 30 km, and to the new port construction in Therma and extension of the main port in Kamariotissa. At these points in time, substantial amounts of non-metallic minerals had to be imported from the mainland. By excluding the aforementioned peaks, the island's maximum *total system throughput* value (Table 1 and Fig. 3d) occurred before the Greek debt crisis (541 kt in 1996) and declined afterwards (reaching 386 kt in 2019).

Over the years, the island entered the *"window of efficiency"* (Fig. 4a and b) the properties of which are explained in Appendix C. The two points in Fig. 4a which fall outside the *"window of efficiency"*, and which have the lowest *number of roles* of 3.8 and 3.9, correspond to the peak years of 1990 and 1970, respectively. The maximum *number of roles* was 4.4 in 1959. In terms of *number of links*, the minimum and maximum values attained were 1.1 in 1938 and 1.3 in 2011, respectively (Table 1). Overall, the *number of links* between the socio-economic metabolic processes increased throughout the decades due to a slowly growing *overhead* (i.e., redundancy in network connections). This was the result not so much of forming new links between the various metabolic processes but rather of increased flows in socio-economic cycling and material stock creation.

The *robustness* of Samothraki remained well below the maximum value which is located within the *"window of vitality"* (Fig. 4b and c) despite its relative improvement over these 90 years. The *"window of vitality"* translates into a range of *degrees of order* (between approximately 0.2 and 0.5) which has been observed to describe healthy natural ecosystems (Ulanowicz, 2020). The limited *robustness* is clearly due to the linear structure of the island's metabolism which is in line with previous research and seems to be typical of systems that are driven by external factors (Chatterjee et al., 2022; Chatterjee et al., 2021a, b; Fath et al., 2019). From the perspective of ascendency analysis, when the socio-economic metabolism of Samothraki is compared to the performance of a natural ecosystem, it can be considered as unsustainable, potentially brittle against shocks, despite the limited increase in its *robustness* over the years.

3.2. Results from ecological network analysis

The mild increase in the *average path length* by approximately 1% (Fig. 5a) in combination with a considerable increase in *total system throughput* by 224% (Table 1) suggests that the metabolism of Samothraki over these 90 years did not improve substantially its ability to generate internal flow activity per unit input of resources regardless of the overall increase both in its *capacity to develop* as well as in its *robustness*. This was primarily the result of the heavy dependence of the island on non-renewable, external input material flows which increased by 222% (Table 1 and Fig. 3d). The lack of internal cycling of resources is highlighted by the very low values of *Finn's Cycling Index* (FCI) which started to increase only from 1967 onwards, and which remained at very low levels up until 2019 with the exception of two maxima of approximately 1.5% in 1984 and of 1.8% in 1996 (Table 1 and Fig. 5b). These low levels indicate that there is much room for improvement in increasing reuse and circularity. Here, we note that there is no clear relationship between the calculated FCI values, and the input and output cycling rates reported by Noll et al. (2022). This likely due to the different way of computation as the former indicator is based on

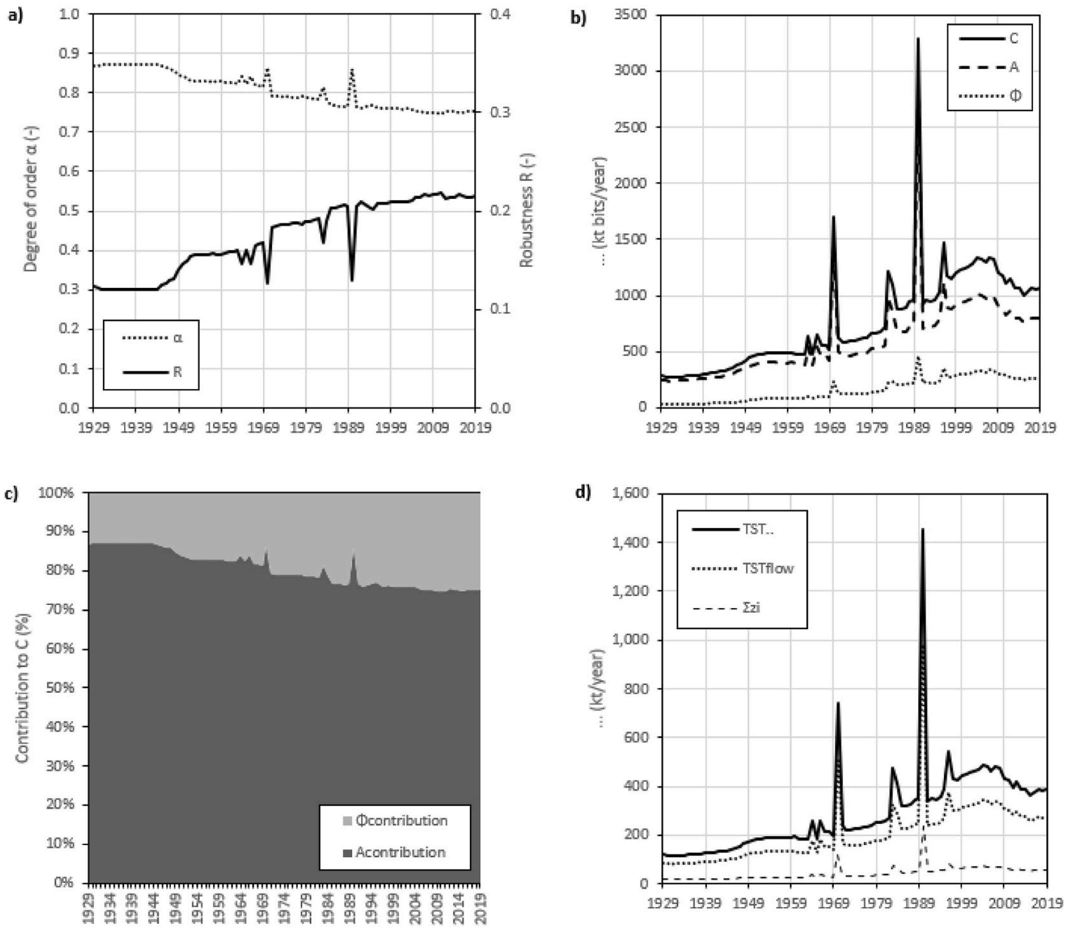

Fig. 3. a) Degree of order (α) and robustness (R) of Samothraki over time, b): ascendency (A), overhead (Φ), and capacity of the island to develop (C), c) contribution of ascendency and of overhead to the total capacity of the island to develop, and d) total system throughput ($TST_{..}$), internal flow total system throughput (TST_{flow}), and boundary input flows (Σz_i).

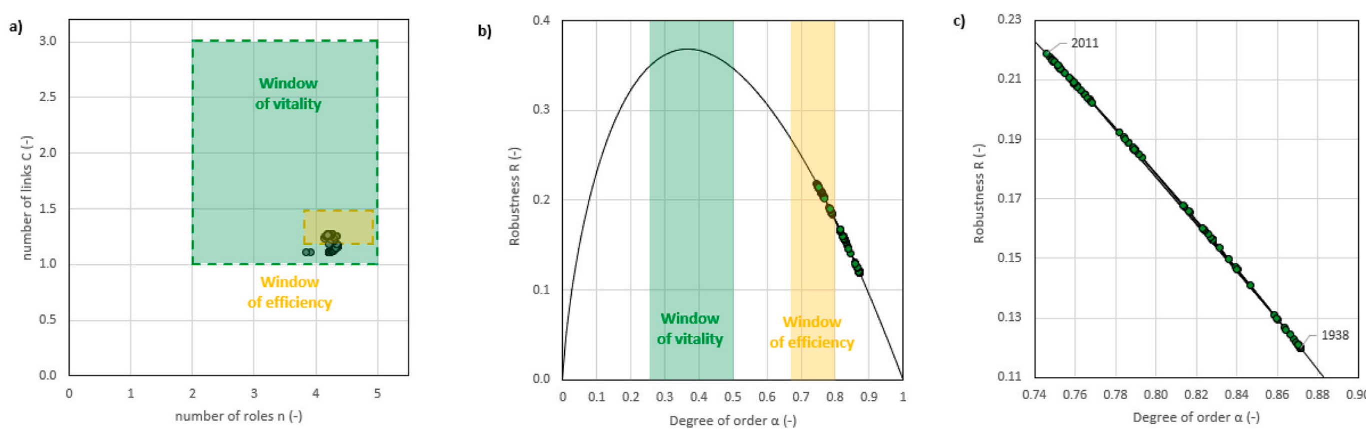

Fig. 4. a) Comparison of the *"window of vitality"* (Ulanowicz, 2009) with the *"window of efficiency"* (Zisopoulos et al., 2022a, b), b) robustness curve, c) zoom-in of robustness curve.

network theory and the latter on the theory of SMR (data not shown).

Interestingly, the *indirect effects* of resource flows were constantly dominant (DI≫1) for these 90 years accounting for about 65% of the total flow activity on average and reaching a maximum of 69% in 2014 (Fig. 5c). The high value of *indirect effects* is surprising since those are considered desirable in natural ecosystems, leading to an effect which is known as *"network non-locality"* (Fath, 2012). The analysis also showed (Fig. 5c) that between 1929 and 1970 the various metabolic processes were mutualistic (M > 1). However, this *mutualism* was substantially reduced throughout the years in a stepwise manner with a first drop after 1970 and a second drop after 2010, showing an overall decrease of −22%. The *synergism* between the processes was positive but remained constant over these 90 years at values very close to unity, showing only a mild overall decrease by −1%. Such low values of *synergism* are not typically encountered in natural ecosystems, especially in cases where *indirect effects* are relatively high and where *mutualism* values are higher

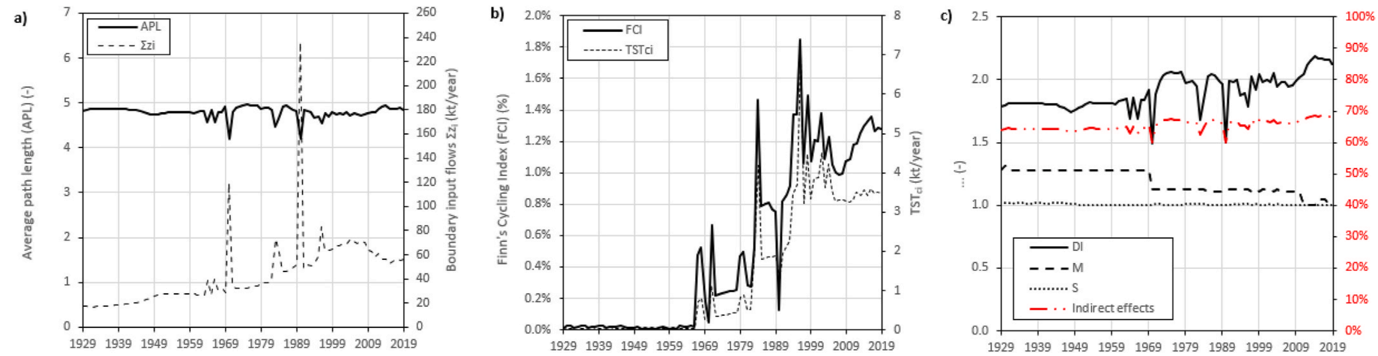

Fig. 5. a) Average path length and total input flows, b) Finn's Cycling Index, and c) Indirect effects, degree of mutualism, and degree of synergism.

than one. This is possibly due to the linear structure of the studied network with limited feedback loops which restrict the interconnectivity between the various socio-metabolic processes.

3.3. Results from scenario analysis

Table 2 shows the results from the scenario analysis. Even though scenarios 1 and 2 do lead to a substantial reduction in DMC and DPO (Noll et al., 2022), the impact of these measures on the network properties of the socio-economic metabolism of the island is limited. The measures affect mainly: a) the island's capacity to develop (by −27% and by −30%, respectively), due to b) a reduction in ascendency (by −27% and by −30%, respectively) and a reduction in overhead (by −27% and by −31%, respectively), c) its value of robustness (by +0.15% and by −0.23%, respectively), d) its degree of cycling as described by FCI (by −0.02% and by +0.02%, respectively), e) the indirect flow effects as described by DI (by −1,14% and by −1.12%, respectively), f) the degree of mutualism (by −1.09% in both scenarios), and g) the degree of synergism (by +1,13% and by +1,11%, respectively).

Scenario 3 reduces the values of some indicators but overall, it has more beneficial effects when compared to the other scenarios. The negative effects are related to the reduction: a) in the number of roles by approximately −8.1%, and b) in the island's capacity to develop by −2%. The positive aspects of this scenario are that: a) the number of links is increased by 16.1%, b) and as a result, the disordered part of the network (H_c) which provides resilience, is increased by 62.8%, c) leading to a reduction in the degree of order by −15.4%, d) and an increase in the robustness by 34%, e) the total flow activity per unit input (APL) is increased by 33.6%, f) the internal cycling of resources (FCI) is increased by 15.1%, g) the indirect effects are increased by 11.4%, h) the degree of mutualism is increased by 32.9%, and i) the degree of synergism is increased by 4.2%. Overall, and despite the mentioned downsides, such an interconnected network structure could theoretically boost resilience and induce considerably more internal cycling of resources as regenerative re-investments when compared to scenarios 1 and 2.

Table 2
Results from scenario analysis compared to the values of 2019.

Principle	Symbol	Units	2019	Scenario 1	Scenario 2	Scenario 3
Cross-scale circulation	Σz_i	kt/year	56	41	39	40
	TST.	kt/year	386	280	269	339
	TST_{flow}	kt/year	273	198	190	259
	APL	–	4.9	4.9	4.8	6.5
Regenerative re-investments	FCI	%	1.3%	1.3%	1.3%	16.4%
Balance between efficiency & resilience	X	bits	2.1	2.1	2.1	1.9
	H_c	bits	0.7	0.7	0.7	1.1
	H	bits	2.8	2.8	2.7	3.1
	A	kt bits/year	799	580	556	661
	Φ	kt bits/year	264	192	183	378
	C	kt bits/year	1063	772	740	1039
	α	–	0.751	0.751	0.752	0.636
	R	–	0.215	0.215	0.214	0.288
Sufficient number & diversity of roles	n	–	4.2	4.2	4.2	3.9
	c	–	1.3	1.3	1.3	1.5
Degree of mutualism	Direct flow	–	8	8	8	8
	Total flow	–	25	24	25	39
	Indirect flow	–	17	17	17	31
	DI	–	2.1	2.1	2.1	3.9
	Indirect effects	%	68%	68%	68%	79%
	M	–	1.000	0.989	0.989	1.329
	S	–	1.002	1.013	1.013	1.044

4. Discussion

The transition of islands to a CE can be facilitated with the adoption of circular practices not only by improving solid waste management through recycling and resource recovery (Kowlesser, 2020) and by coupling the emerging CE ecosystems with renewable energy sources (Kiviranta et al., 2020) but also by improving the tourism industry which can function as a catalyst (Schumann, 2020). Furthermore, relevant practices can be integrated into existing legal and policy frameworks, where the local governments are to raise awareness of their existence by utilizing waste management to improve the overall resource use efficiency and by encouraging businesses to adopt business models which place the restoration of nature at the heart of local economic activities (Andriamahefazafy et al., 2022; Singh et al., 2023). In support of evidence-based policy and planning, quantitative methods from SMR and regenerative economics can offer a dashboard of key monitoring indicators.

4.1. The results in context

Our study highlights that to get a better understanding of the regenerative potential of a socio-economic system (in this case, an island), all indicators which have been studied here need to be considered simultaneously and together with the system's historical context. Similar suggestions were given also by researchers who studied the water flux configuration of the Keriya Oasis in Northwestern China (Muhtar et al., 2021). They found that the studied network increased its resilience and became more structurally robust over the years, albeit at the expense of functional effectiveness, or, in other words, declining water-related benefits, and suggested that when analyzing such systems both aspects should be addressed (Muhtar et al., 2021). In another case, researchers compared different industrial symbiosis scenarios at Sötenas in Sweden and proposed that both the system's structural *robustness* (which was affected by its network topology) and its environmental performance [i.e., in terms of global warming potential (quantity of CO_2 equivalent), terrestrial acidification (quantity of P equivalent), and freshwater eutrophication (quantity of N equivalent) which were affected mainly by the system's complexity], should be considered simultaneously during decision-making processes, even as independent evaluation criteria manifesting as trade-offs (Barrau and Glaus, 2023).

These two examples support the argument that multi-indicator consideration is important in regenerative economics. In general, a more interconnected network is expected to perform better than one which has a more linear structure (at least theoretically), but its overall performance will depend not only on the number of connections between its nodes but also on the way those are connected. Complexity can give rise to innumerable scenarios with different network structures and therefore general rules of thumb on *"appropriate"* values for all the indicators studied here, are difficult to suggest, especially given the lack of studies on this very topic. This further highlights the need for more research to be conducted on other islands.

When the performance of the socio-economic metabolism of Samothraki is assessed only in terms of its *number of roles* and of *number of links* then the results from ascendency analysis indicate that it fits within the *"window of vitality"*. Furthermore, the *number of roles* for Samothraki happens to range between approximately three and five which seemingly aligns with the values of trophic levels observed in natural ecosystems. Then, the conclusion that one could draw just by looking at these two indicators would be that Samothraki is sustainable having sufficiency in diversity of roles for proper system functioning. However, such a conclusion can be misleading, and it should be validated by looking also how the network performs on a robustness curve when plotting its *degree of order* versus its *robustness*.

Moreover, our analysis highlights that the indicators from ascendency analysis alone are also not sufficient for providing a holistic picture. If the results of ascendency analysis are examined in isolation, they can give the impression that there was a substantial improvement on the socio-economic metabolism of Samothraki, particularly in terms of its *capacity to develop* and its *robustness* between 1929 and 2019. This reasoning aligns logically with the overall progress that was brought to the island by the development of infrastructure, by the modest tourism development, and by the alternative sources of income due to labor migration to the mainland. However, this explanation is valid only up to a certain extent given the various problems which the island has been experiencing over the past decades. The island is now more dependent on imports for food, feed, and construction materials which do not only increase waste challenges, but also socio-metabolic risks associated with the reliance on external markets (Noll et al., 2022; Singh et al., 2022). One of the most pressing environmental problems is triggered by the socio-ecological crisis of the local farming system whereby large numbers of sheep and goats overgraze the island's ecosystems while farmers rely largely on subsidies and are not able to sell their products for reasonable prices (Fischer-Kowalski et al., 2020; Noll et al., 2020). Additionally, the increasing amounts of solid waste due to changing consumption patterns and maintenance requirements of the large material stock are also posing great challenges to the island community (Noll et al., 2019). Such complexity calls for a trans-disciplinary approach by combining different *"methods to gain more insights on how to transition effectively from a linear to a circular economy"* (Walzberg et al., 2021).

4.2. Samothraki towards a regenerative state

The scenario analysis highlighted two aspects. The first one is that measures such as cutting out fossil fuels and limiting biomass extraction via grazing and wood extraction (scenarios 1 and 2), would not lead to large improvements on the studied network properties of the island's metabolism. However, it would be inaccurate to conclude that such measures are not important given that they could reduce DMC and DPO considerably, as SMR has shown (Noll et al., 2022). The reason why these measures had limited impact in the present study is because the quantitative methods used are pertinent both to structural information of the network (expressed by the existence or absence of flows between its nodes) as well as to flow-magnitude information (expressed by the size of flows between its nodes). The measures in the scenarios affected mainly the sizes of flows rather than the number of links between the processes of the (static) linear socio-economic metabolism of Samothraki, and that is why they had limited impact on its network properties. Here, it is also important to note that the proposed measures are specific for Samothraki given that the island still relies largely on biomass. Such measures would be also highly relevant for other economies where fossil fuels are a big problem since they are per se uncircular and generate carbon emissions. Substituting out fossil fuels would also have a bigger positive impact on two RE principles not otherwise considered here, which are about reliable inputs and healthy outputs. These principles will be explored in future research.

The second aspect is that the network properties of Samothraki's metabolism could be improved substantially when a combination of circularity measures, of waste hierarchy principles (e.g., reduce, reuse, refurbish etc.), and of changes in production and consumption patterns would be considered simultaneously (scenario 3). Regardless of the reduction in the values of some indicators, such a combination of measures would theoretically lead to a more interconnected (i.e., developed) network allowing for more internal resource flow activity to be generated and circulated with reduced inputs. This is particularly visible by the considerable increase both in the *average path length* (also known as network aggradation) by 33.6% as well as in *Finn's cycling index* by 15.1%. The former indicator is analogous to the *multiplier effect* in economics assessing *"how many times a unit of currency entering a market will be exchanged before exiting that market"* (Fath et al., 2019a,b) and the latter indicator captures higher internal re-use of resources but which, in general, should be handled with care since a high value could also indicate a system under stress, highlighting the importance of knowledge of the local context (Fath et al., 2019a,b). Here, for the sake of simplification purposes, the interconnected flows of scenario 3 were considered in an unspecified manner which admittedly would demand substantial changes in local production and consumption patterns and novel ways of dealing with waste. But what first steps could the local society take to start thinking about the implementation of such measures?

One way could be through the adoption of circular business models (CBMs)[1] which follow the waste hierarchy principles to create, capture, and deliver value. The main strategies of these models are about closing, slowing, narrowing, intensifying, substituting, or dematerializing loops of material and energy flows via the digitalization and selling of services instead of products (Geissdoerfer et al., 2020). However, this argument needs to be treated with care. Even though we do not have readily available a GDP growth curve for the island, so far, its *"service society"* did not achieve a complete decoupling of economic growth and resource

[1] Circular business models are a type of sustainable business models which *"integrate environmental and economic value creation (Bocken et al., 2016; Lieder and Rashid, 2016) by generating profits from a continual flow of reused materials and products over time (Bakker et al., 2014a) and by capitalising on the value embedded in used products (Achterberg et al., 2016; Linder and Williander, 2017)"* (Guldmann et al., 2019)

use as most services are still coupled to energy and material use [like on a global scale (Wiedmann et al., 2020)]. The focus must thereby be not only on the shift towards a *"service society"* but on the reduction of overall resource consumption and on closing the loop for all used materials.

Improving trade with the mainland via exports could also be an important aspect of CBMs. An increase in the exports of biomass in the form of agricultural products could theoretically increase farmers' income and help them to lower their animal numbers and reduce extraction of natural resources. But more exports could also lead to the opposite effect i.e., to an increase of domestic extraction of natural resources due to profitable business opportunities. Therefore, the goal in such a case would be to address the challenge of reducing domestic extraction as well as of imports while simultaneously improving marketing opportunities without causing another phase of biophysical growth.

In an island context, barriers and enablers to a CE can be highly contextual depending on territorial dynamics and therefore any interventions should be *"place-based, tailored and coherent, avoiding regulatory conflicts, capitalizing on local strengths, and building on local assets"* (Sciacca, 2020). In general, a successful transition of an island to a CE will depend on: a) the formulation, adoption, and implementation of effective policies, b) on behavioral changes related to local production and consumption patterns, and c) on the ability of stakeholders to adopt CBMs with different specializations and to form inclusive collaborative partnerships for the efficient cross-scale circulation of resources. Undeniably, this is something which is not easy to achieve domestically in such small economies.

4.3. Methodological aspects and the economy-as-an-organism analogy

This study showed that ecological network analysis and ascendency analysis can complement SMR by providing additional information on the regenerative potential of the socio-economic metabolism of an island and by comparing alternative scenarios relevant for a transition to a CE. Both network-based methods can be considered as scientifically valid to follow the economy-as-an-organism analogy since they conform with the eight propositions of Makriyannis (2022).

- They can quantify a network's structural properties demonstrating **structure mapping (proposition 1).**
- They describe a socio-economic metabolism as a network of mutually constraining interconnected metabolic processes providing **mapping clarity (proposition 2).**
- They are based on thermodynamics and information theory whereby both the base domain (natural ecosystems) and the study domain (socio-economic metabolism) have adequate similar characteristics, and therefore exhibit **base specificity (proposition 3).**
- They follow the **systematicity principle (proposition 4)** given that *"the systemic nature of organisms and economies has hardly ever been questioned by the scientific community"* (Makriyannis, 2022).
- They summarize metabolic interrelations into target equations and indicators to capture regenerative aspects and can be used to **assess whether universal laws which apply in natural ecosystems also apply in socio-economic systems (proposition 5).**
- They need to be used in tandem and along with knowledge of the local context to **provide novel perspectives (proposition 6)** and lead to **goal-relevant inferences (proposition 7).**
- They are **logically aligned with SMR (proposition 8)** since they generate results in agreement with facts which have already been discovered about economies despite applying a different perspective.

4.4. Directions for future studies

Given the relevance and methodological validity of these network-based tools which can offer complementary insights to SMR specifically for the quantification of regeneration properties of socio-economic systems, we propose that future research should:

- address how to model socio-economic systems beyond **steady state** which is currently a methodological requirement of network analysis.
- standardize the **conceptualization of a socio-economic system** as a network which is currently left to the discretion of the researcher. For example, a **metabolic approach** (as the one followed here) assumes that the network of the socio-economic system has a linear structure populated mainly by sequential rather than parallel or interlinked processes. It is reasonable then to expect that such a linear system would tilt towards the brittle side of the robustness curve i.e., more towards the *"window of efficiency"* (discussed in Appendix C). Recent research suggests that for such linear metabolic socio-economic structures there might be limits to *robustness* possibly due to modelling choices where the system is studied as a chain of processes with limited number of feedback loops (Zisopoulos et al., 2022a, b). On the other hand, a **sectorial approach** for analyzing a socio-economic system (where the nodes would, for example, represent tourism, agriculture, industry, etc.) could lead to a more interconnected network which would be expected to lean more towards the resilient side of the *"window of vitality"* (Kharrazi et al., 2013; Scharler et al., 2018).
- standardize the consideration of additional linkages or feedback loops between socio-metabolic processes during **scenario planning.**
- explore how to capture the other five **principles of RE** from the framework of Fath et al. (2019a,b) by acknowledging that the use of quantitative network-based methods, while clearly useful, it is not sufficient for grasping the intricacies of human-made systems. Those principles are: 1) reliable inputs, 2) healthy outputs, 3) balances of sizes, 4) constructive versus extractive processes, and 5) collective learning. The integration and operationalization of all ten principles in a systematic and rigorous way will allow for a more holistic approach to be followed when analyzing socio-economic systems.
- verify whether other socio-economic systems follow similar patterns with the one discussed here.

We believe that due to its comprehensiveness, regenerative economics will become an even more prominent scientific field, contributing with tools and theories on regeneration which will be useful to a plurality of stakeholders including policy makers, local authorities, and researchers.

5. Conclusions

We studied the regenerative potential of the island of Samothraki in Greece by using principles from regenerative economics. We captured those principles with metrics from information-based and flow-based ecological network analyses to analyze the socio-economic metabolism of Samothraki by using data from Noll et al. (2022).

Overall, the results of ascendency analysis showed that Samothraki had an increasing trend in its *robustness* over 90 years. Its value however remained at relatively modest levels for the past decade, and well below of what is typically observed for healthy natural ecosystems (i.e., the *"window of vitality"*). The increase in Samothraki's *capacity to develop* was mainly due to the quantitative growth of the ordered part of its linear metabolism (i.e., due to the increase in the *total system throughput* of resources) which endowed it with efficiency in streamlining imported resources. The disordered part of the island's socio-economic metabolism, which is related to its *resilience*, played a considerably smaller yet progressively more important role over the past decades.

Ecological network analysis showed that Samothraki had a very low ability to generate internal flow activity and cycling of resources per unit input as measured both by the *average path length* and by *Finn's Cycling Index*. This was due to the island's dependency on imports but also due to its assumed linear socio-economic metabolic structure with limited number of feedback loops in its network.

The analysis of scenarios 1 and 2 showed that the implementation of the measures proposed by Noll et al. (2022) would theoretically improve some of the network-based indicators compared to 2019, albeit to a limited degree. Here we note that these measures are very important in that they could reduce DMC and DPO substantially, as SMR has previously shown. The seemingly limited improvement in the present analysis is because these measures influence mainly the sizes of flows of the socio-economic metabolism of the island, affecting the quantitative and growth-related elements (rather than the qualitative and development-related elements) of its network properties. In scenario 3, the implementation of these measures along with the adoption of waste hierarchy principles by local stakeholders (e.g., local government, small and medium enterprises, organizations etc.) in their organizational and operational processes (e.g., through CBMs), and a change in production and consumption patterns, would affect both the quantitative and the qualitative properties of the network. In this case, and regardless of the reduction in the values of some indicators (e.g., *number of roles* and *capacity to develop*), a more interconnected and mutualistic socio-economic metabolism would emerge. Such a reticulated network structure would theoretically endow the island with increased *resilience* and *robustness*, allowing for more internal resource flow activity to be circulated as regenerative re-investment.

Our study shows that while SMR provides valuable information on the types and sizes of flows and stocks through an island's metabolism over the years, network-based methods from regenerative economics offer complementary indicators. These consider simultaneously both growth and development components of its metabolic structure and can be used as diagnostic tools to quantify properties such as *resilience*, *robustness*, and *degree of mutualism*. Both utilized methods are scientifically valid to follow the island economy-as-an-organism analogy, and therefore they can complement SMR. They can be used to assess and monitor the impact of strategies related to circular economy interventions on network properties, illuminating their influence on the regenerative potential of an island. We stress that it is equally important to consider the local historical context in a holistic manner, and hence a transdisciplinary approach is not just useful but necessary.

If the transition to a circular economy is the way forward, then it should be accomplished in ways which benefit people and the environment where regeneration has a primary rather than a tertiary role for supporting the sustainable development of islands.

Credit author statement

F.K.Z. conceived of the idea of the research, compiled the document structure, formal analysis, writing of the original draft, conducted the quantitative analysis, and wrote the text as the main author. D.N: provided data along with background history on the island's context of development as well as knowledge on circular economy, S.S: provided data along with background history on the island's context of development as well as knowledge on circular economy, D.S.: provided knowledge on circular economy and infrastructure management, M.d.J. provided knowledge on aspects of social inclusion and public administration, B.D.F.: Methodology, provided knowledge for the methodologies of regenerative economics, S.G.: Methodology, provided knowledge for the methodologies of regenerative economics, D.F.: Methodology, provided knowledge for the methodologies of regenerative economics, R.E.U.: Methodology, provided knowledge for the methodologies of regenerative economics, K.W. provided critical reflection on circular economy aspects. All authors contributed significantly to this work by reading, knowledge-sharing, providing constructive criticism, editing, and reviewing the text, All authors have read and agreed to the published version of the manuscript, The authors are also grateful to three anonymous reviewers and to Dr. Bruno Meirelles for their time and effort in providing critical comments.

Funding

The authors are grateful to the *Impact for Sustainability* Fund, a named fund at *Stichting Erasmus TrustFonds*, for funding this research (project number: 97090.2022.101.671/074/RB). The study falls within the Sino-Dutch project *"Towards Inclusive CE: Transnational Network for Wise-waste Cities (IWWCs)"* which is one of the projects of the *Erasmus Initiative Dynamics of Inclusive Prosperity*, and it is co-funded by the Dutch Research Council (NWO) and the National Natural Science Foundation of China (NSFC); NWO project number: 48219608; NSFC project number: 72061137071.

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.

Data availability

The data and analysis are to be made available open access along with this paper. Excel file.

Abbreviations and symbols

A	Ascendency or efficiency or ordered part (scaled)
APL	Average path length
c	Number of links
C	Capacity for development (scaled)
CE	Circular economy
DE	Domestic extraction of natural resources
DMC	Domestic material consumption
FCI	Finn's cycling index
H	Capacity for development (unscaled)
H_c	Redundancy or overhead or resilience (unscaled)
M	Degree of mutualism
n	Number of roles
R	Robustness
RCV_R	Amount of recovered materials
S	Degree of synergism

$U_{circular}$	Amount of circularly used materials
TST	Total system throughput
α	Degree of order
X	Average mutual information or efficiency or ordered part (unscaled)
Φ	Redundancy or overhead or resilience (scaled)

Appendix A

Island of Samothraki in Greece (Google Maps, 2022).

Appendix B

Equations used.

$$DMI = IMP + DE$$

$$DMC = DMI - EXP$$

$$PM = DMC + SEC$$

$$Interim\ Outputs = eUse + TM + DD$$

$$GAS = mUse - TM + GAS\ humans\ and\ livestock$$

where

$IMP = imports$

$EXP = exports$

$DMI = domestic\ material\ input$

$PM = processed\ material$

$DMC = domestic\ material\ consumption$

$SEC = socioeconomic\ cycling$

$eUse = energy\ use$

$mUse = material\ use$

$TM = throughput\ material$

$DD = demolition\ and\ discard$

$GAS = gross\ addition\ to\ stocks$

Appendix C

Reflecting on the meaning of network properties

Capacity to develop: In the context of ascendency analysis, a high value in the capacity of a socio-economic metabolism to develop is not related to economic growth but to the maximum *ascendency* which could be achieved theoretically. In other words, the *capacity to develop* is the ability of a socio-economic system to evolve its network of interconnected processes by considering simultaneously the constraints of its metabolic pathways as well as the size of resource throughflow.

Degree of order: The interconnected links between the processes of the socio-economic metabolism summarize operations at the local scale of the island which include the extraction, production, and import of products and resources, as well as their exchange, export, and consumption. Therefore, the ability of streamlining efficiently these resources through each node of the socio-economic metabolism in a largely linear and sequential manner implies that the island has a high *degree of order* (i.e., network efficiency). In this way, resources flow throughout the socio-economic metabolism, from their entry point to the socio-economic system of the island in the form of imports and extracted resources up to their exit point in the form of exports or emissions and waste. Therefore, a high *degree of order* in ascendency analysis is typically the result of a linear network structure which comes at the risk of increased brittleness towards shocks due to lacking sufficient feedback loops.

Resilience: By creating more links and feedback loops between the various processes of a socio-economic metabolic network, its *resilience*, and therefore its overall *robustness*, could theoretically increase. This, of course, depends on the way the system is modelled, meaning that it is subject to methodological constraints.

Robustness: This property has been defined in literature in a broad context as *"the probability of a system to maintain its identity and not cross an undesirable (possibly irreversible) threshold following one or more adverse events*[33-34]*"* (Grafton et al., 2019, p. 908). Here, *robustness* is understood as the system's buffer capacity or ability of balancing the diversion of resource flows during a shock while simultaneously maintaining vital functions and avoiding collapse.

Socio-metabolic collapse: Within the SMR context, socio-metabolic collapse *"is characterized by the failure of the society's ability to organize its own social metabolism without external aid, and to govern its recovery by interfering with its cultural, economic, and political regulation"* and *"refers only to the breakdown of society's social metabolism"* (Singh et al., 2022, p. 3).

Window of vitality: This is a conceptual abstraction theorized to describe healthy natural ecosystems (i.e., ecological *"window of vitality"*) as defined by the rectangular area formed when the range of *number of roles* of a studied network is plotted against its range of *number links* (Ulanowicz, 2009; Ulanowicz et al., 2009; Zorach and Ulanowicz, 2003). When natural ecosystems are studied using ecological network analysis, their nodes describe different species (or an aggregated grouping of species) as compartments at different trophic levels (Fath et al., 2007). The minimum *number of roles* in natural ecosystems is at least two given that *"the very definition of an ecosystem that it encompass complementary processes, such as oxidation/reduction reactions or autotrophy/heterotrophy interactions (*Fiscus, 2001*)"* (Ulanowicz et al., 2009). The maximum *number of roles* in natural ecosystems is assumed arbitrarily to be five based on the logic that trophic pathways with more than five levels (i.e., producers, primary, secondary, tertiary, and quaternary consumers) seem to be uncommon (Ulanowicz et al., 2009). Furthermore, the nodes of networked ecosystems are assumed to have at least one linkage with another node (i.e., $c \geq 1$), otherwise, they would describe non-communicative (i.e., segregated) sub-networks (Ulanowicz et al., 2009). The higher value of the *number of links* (i.e., $c \sim 3.01$) stems from the May-Wigner stability hypothesis from information theory whereby *"systems can be either strongly connected across a few links or weakly connected across many links, but configurations of strong connections across many links and weak connections across a few links tend to break up or fall apart, respectively (May 1972)"* (Ulanowicz et al., 2009). The values of the *number of links* and *number of roles* can be translated into a range of *degrees of order* between approximately 0.2 and 0.5 which corresponds to a range of *robustness* values observed for healthy natural ecosystems i.e., around 0.36 (Ulanowicz et al., 2009). It has also been suggested that this range of *degrees of order* covers a slightly broader spectrum between approximately 0.21 and 0.59 (Chatterjee et al., 2021a, b; de Souza et al., 2019; Layton, 2014, 2022). The shape of the robustness curve is due to Ludwig Boltzmann's formula which has a fundamental role in the theoretical underpinning of ascendency analysis, and it *"is heavily skewed towards imparting more weight to rare events"* whereby *"the product $p_i log(p_i)$ becomes a joint measure of both the presence and absence of event i"* (Ulanowicz, 2020). The shape of the curve also supports the hypothesis that natural ecosystems tend to grow and develop by utilizing their resources efficiently under stable conditions but can still recover when faced with shocks due to redundancy in their connections (Ulanowicz, 2009).

Window of efficiency: This window is a conceptual abstraction theorized to describe the growth and development of human systems, and it is based on findings from a recent study on the material and energy flow metabolism of the EU27 Member States between 2010 and 2018 by using Eurostat data (Zisopoulos et al., 2022a, b). More specifically, the *"window of efficiency"* intends to capture the tendency of human-made systems for optimizing the efficient streamlining of resources through the various processes of their socio-economic metabolism rather than establishing reliable feedback loops for greater resilience. Here, we explain how this window was identified in that study whereby the nodes of the networks studied represent socio-economic processes. In SMR these processes are typically related to the extraction of natural resources, imports, domestic material consumption, exports etc. Particularly for the material flow metabolism of the EU27, the *number of roles* has been found to range between approximately 3.82 and 4.92 and the *number of links* between approximately 1.19 and 1.48. By recalibrating the robustness curve for the corresponding data, the *degree of order* was found to range between approximately 0.6 and 0.8, indicating a maximum robustness value for these material flow networks of 0.280, which is considerably lower than what is observed for robust natural ecosystems. The formula $R_{adj} = \gamma[\alpha^{\beta}\, ln(\alpha^{\beta})]$ was used for the recalibration whereby the estimated beta and gamma values were 3.0114 and 0.7611, respectively. However, it is stressed that the beta and gamma values have no physical meaning as they were only used to adjust the shape of the robustness curve to match the data. Similar values were observed in that study for the energy flow metabolism of the EU27 for the same period.

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.137136.

References

Andriamahefazafy, M., Benkenstein, A., Failler, P., 2022. *Unlocking The Circular Economy Potential of African Island States: Policy Insights* (Issue July). South African Institute of International Affairs (SAIIA), Johannesburg, South Africa. https://saiia.org.za/research/unlocking-the-circular-economy-potential-of-african-island-states/.

Barrau, E., Glaus, M., 2023. Structural and environmental performance of evolving industrial symbiosis: a multidimensional analysis. Sustainability 15 (1). https://doi.org/10.3390/su15010693.

Chatterjee, A., Huang, H., Davis, K.R., Layton, A., 2021a. A multigraph modeling approach to enable ecological network analysis of cyber physical power networks. In: 2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids. SmartGridComm 2021, pp. 239–244. https://doi.org/10.1109/SmartGridComm51999.2021.9631989.

Chatterjee, A., Malak, R., Layton, A., 2021b. Exploring system of systems resilience versus affordability trade-space using a bio-inspired metric. J. Comput. Inf. Sci. Eng. 21 (5), 050905 https://doi.org/10.1115/1.4050288.

Chatterjee, A., Malak, R., Layton, A., 2022. Ecology-inspired resilient and affordable system of systems using degree of system order. Syst. Eng. 25 (1), 3–18. https://doi.org/10.1002/sys.21598.

Chertow, M.R., 2008. Uncovering" industrial symbiosis. J. Ind. Ecol. 11 (1), 11–30. https://doi.org/10.1162/jiec.2007.1110.

Dave, T., Layton, A., 2020. Designing ecologically-inspired robustness into a water distribution network. J. Clean. Prod. 254 (1), 120057 https://doi.org/10.1016/j.jclepro.2020.120057.

de Jonge, V.N., Schückel, U., 2021. A comprehensible short list of ecological network analysis indices to boost real ecosystem-based management and policy making. Ocean Coast Manag. 208 https://doi.org/10.1016/j.ocecoaman.2021.105582.

de Souza, V., Bloemhof-Ruwaard, J., Borsato, M., 2019. Exploring ecosystem network analysis to balance resilience and performance in sustainable supply chain design. Int. J. Adv. Oper. Manag. 11 (1–2), 26–45. https://doi.org/10.1504/IJAOM.2019.098525.

Eckelman, M.J., Ashton, W., Arakaki, Y., Hanaki, K., Nagashima, S., Malone-Lee, L.C., 2014. Island waste management systems. J. Ind. Ecol. 18 (2), 306–317. https://doi.org/10.1111/jiec.12113.

Elgie, A., 2022. *Trash Is Just Treasure in the Wrong Place: The Social Metabolism of Waste in Grenada* [PhD Thesis. University of Waterloo. https://uwspace.uwaterloo.ca/handle/10012/17828.

Elgie, A.R., Singh, S.J., Telesford, J.N., 2021. You can't manage what you can't measure: the potential for circularity in Grenada's waste management system. Resour. Conserv. Recycl. 164, 105170 https://doi.org/10.1016/j.resconrec.2020.105170.

Ellen MacArthur Foundation, 2019. The Circular Economy in Detail. Available from: www.ellenmacarthurfoundation.org. (Accessed 28 February 2023) https://archive.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail.

Fath, B.D., 2012. Overview of network Environ analysis - a systems technique for understanding complex ecological systems. Ecol. Quest. 16, 77. https://doi.org/10.12775/v10090-012-0008-0.

Fath, B.D., 2018. Systems Ecology: Ecological Network Analysis. Encyclopedia of Ecology, second ed., vol. 1, pp. 643–652. https://doi.org/10.1016/B978-0-12-409548-9.11171-6

Fath, B.D., Asmus, H., Asmus, R., Baird, D., Borrett, S.R., de Jonge, V.N., Ludovisi, A., Niquil, N., Scharler, U.M., Schückel, U., Wolff, M., 2019a. Ecological network analysis metrics: the need for an entire ecosystem approach in management and policy. Ocean Coast Manag. 174, 1–14. https://doi.org/10.1016/j.ocecoaman.2019.03.007. July 2018.

Fath, B.D., Fiscus, D.A., Goerner, S.J., Berea, A., Ulanowicz, R.E., 2019b. Measuring regenerative economics: 10 principles and measures undergirding systemic economic health. Glob. Trans. 1, 15–27. https://doi.org/10.1016/j.glt.2019.02.002.

Fath, B.D., Scharler, U.M., 2018. Systems ecology: ecological network analysis. In: Encyclopedia of Ecology, second ed., Issue April. Elsevier Inc. https://doi.org/10.1016/B978-0-12-409548-9.11171-6.

Fath, B.D., Scharler, U.M., Ulanowicz, R.E., Hannon, B., 2007. Ecological network analysis: network construction. Ecol. Model. 208 (1), 49–55. https://doi.org/10.1016/j.ecolmodel.2007.04.029.

Fetzel, T., Petridis, P., Noll, D., Singh, S.J., Fischer-Kowalski, M., 2018. Reaching a socio-ecological tipping point: overgrazing on the Greek island of Samothraki and the role of European agricultural policies. Land Use Pol. 76 (March), 21–28. https://doi.org/10.1016/j.landusepol.2018.04.042.

Fischer-Kowalski, M., Löw, M., Noll, D., Petridis, P., Skoulikidis, N., 2020. Samothraki in transition: a report on a real-world lab to promote the sustainability of a Greek Island. Sustainability 12 (5), 1–23. https://doi.org/10.3390/su12051932.

Geissdoerfer, M., Pieroni, M.P.P., Pigosso, D.C.A., Soufani, K., 2020. Circular business models: a review. J. Clean. Prod. 277, 123741 https://doi.org/10.1016/j.jclepro.2020.123741.

Google Maps, 2022. Samothraki. Available from: https://goo.gl/maps/. (Accessed 28 February 2023) https://goo.gl/maps/kameDYehxcFC5rw56.

Grafton, R.Q., Doyen, L., Béné, C., Borgomeo, E., Brooks, K., Chu, L., Cumming, G.S., Dixon, J., Dovers, S., Garrick, D., Helfgott, A., Jiang, Q., Katic, P., Kompas, T., Little, L.R., Matthews, N., Ringler, C., Squires, D., Steinshamn, S.I., et al., 2019. Realizing resilience for decision-making. Nat. Sustain. 2 (10), 907–913. https://doi.org/10.1038/s41893-019-0376-1.

Guldmann, E., Bocken, N., Brezet, H., 2019. A design thinking framework for circular business model innovation. J. Bus. Mod. 7 (1), 39–70. https://doi.org/10.5278/ojs.jbm.v7i1.2122.

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 2 (3), 173–184. https://doi.org/10.1038/s41893-019-0225-2.

Huang, H., Mao, Z., Layton, A., Davis, K.R., 2022. An ecological robustness oriented optimal power flow for power systems' survivability. IEEE Trans. Power Syst. 38 (1), 447–462. https://doi.org/10.1109/TPWRS.2022.3168226.

Iskrzyński, M., Janssen, F., Picciolo, F., Fath, B., Ruzzenenti, F., 2021. Cycling and reciprocity in weighted food webs and economic networks. J. Ind. Ecol. 1–12 https://doi.org/10.1111/jiec.13217.

Kharrazi, A., Rovenskaya, E., Fath, B.D., 2017. Network structure impacts global commodity trade growth and resilience. PLoS One 12 (2). https://doi.org/10.1371/journal.pone.0171184.

Kharrazi, A., Rovenskaya, E., Fath, B.D., Yarime, M., Kraines, S., 2013. Quantifying the sustainability of economic resource networks: an ecological information-based approach. Ecol. Econ. 90, 177–186. https://doi.org/10.1016/j.ecolecon.2013.03.018.

Kiviranta, K., Thomasson, T., Hirvonen, J., Tähtinen, M., 2020. Connecting circular economy and energy industry: a techno-economic study for the Åland Islands. Appl. Energy 279 (September). https://doi.org/10.1016/j.apenergy.2020.115883.

Kowlesser, P., 2020. An overview of circular economy in Mauritius. In: Ghosh, S. (Ed.), Circular Economy: Global Perspective. Springer. https://doi.org/10.1007/978-981-15-1052-6_14.

Layton, A., 2014. *Food Webs: Realizing Biological Inspirations for Sustainable Industrial Resource Networks* (Issue December) [PhD Thesis]. Georgia Institute of Technology.

Layton, A., 2022. Using biological inspiration to guide the design of human networks for resilience. Climate Resilience Academy UM. https://www.youtube.com/watch?v=sPobHdq_wsI, 28 February 2023.

Makriyannis, C., 2022. The foundational economy-as-an-organism assumption of ecological economics : is it scientifically useful? Ecol. Econ. 200 (June), 107541 https://doi.org/10.1016/j.ecolecon.2022.107541.

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., Blengini, G.A., 2019. Measuring progress towards a circular economy: a monitoring framework for economy-wide material loop closing in the EU28. J. Ind. Ecol. 23 (1), 62–76. https://doi.org/10.1111/jiec.12809.

Miatto, A., Schandl, H., Wiedenhofer, D., Krausmann, F., Tanikawa, H., 2017. Modeling material flows and stocks of the road network in the United States 1905–2015. Resour. Conserv. Recycl. 127 (August), 168–178. https://doi.org/10.1016/j.resconrec.2017.08.024.

Muhtar, P., Xia, J., Muyibul, Z., Zihriya, B., Abliz, A., Zhang, M., 2021. Evaluating the evolution of oasis water metabolism using ecological network analysis: a synthesis of structural and functional properties. J. Clean. Prod. 280 (2), 124422 https://doi.org/10.1016/j.jclepro.2020.124422.

Noll, D., Lauk, C., Gaube, V., Wiedenhofer, D., 2020. Caught in a deadlock: small ruminant farming on the Greek Island of samothrace. The importance of regional contexts for effective EU agricultural policies. Sustainability 12 (3). https://doi.org/10.3390/su12030762.

Noll, D., Lauk, C., Haas, W., Singh, S.J., Petridis, P., Wiedenhofer, D., 2022. The sociometabolic transition of a small Greek island: assessing stock dynamics, resource flows, and material circularity from 1929 to 2019. J. Ind. Ecol. 26 (2), 577–591. https://doi.org/10.1111/jiec.13206.

Noll, D., Wiedenhofer, D., Miatto, A., Singh, S.J., 2019. The expansion of the built environment, waste generation and EU recycling targets on Samothraki, Greece: an island's dilemma. Resour. Conserv. Recycl. 150, 104405 https://doi.org/10.1016/j.resconrec.2019.104405, 2019.

Reap, J., Layton, A., 2017. Lessons from living systems for the development of sustainable industrial resource networks. Journal of Energy Challenges and Mechanics 4 (1), 1–10. Available from: https://www.nscj.co.uk/JECM/PDF/4-1-1-Reap-Layton.pdf. (Accessed 28 February 2023).

Research Alliance for Regenerative Economics, 2022. Science for Building Durably Vibrant Human Networks. Available from: https://rare-sci.net/. (Accessed 28 February 2023).

Reynolds, J., Kennedy, R., Ichapka, M., Agarwal, A., Oke, A., Cox, E., Edwards, C., Njuguna, J., 2022. An evaluation of feedstocks for sustainable energy and circular economy practices in a small island community. Renew. Sustain. Energy Rev. 161 (April), 112360 https://doi.org/10.1016/j.rser.2022.112360.

Salomone, R., Cecchin, A., Deutz, P., Raggi, A., Cutaia, L., 2020. In: Salomone, R., Cecchin, A., Deutz, P., Raggi, A., Cutaia, L. (Eds.), Industrial Symbiosis for the Circular Economy - Operational Experiences, Best Practices and Obstacles to a Collaborative Business Approach. Springer Nature Switzerland. https://www.springer.com/gp/book/9783030366599.

Scharler, U.M., Borrett, S.R., 2021. Network construction, evaluation and documentation: a guideline. Environ. Model. Software 140 (February), 105020. https://doi.org/10.1016/j.envsoft.2021.105020.

Scharler, U.M., Fath, B.D., Banerjee, A., Fang, D., Feng, L., Mukherjee, J., Xia, L., 2018. Resilience measures in ecosystems and socio-economic networks. In: Mensah, P., Katerere, D., Hachigonta, S., Roodt, A. (Eds.), *Systems Analysis Approach For Complex Global Challenges* (Issue April. Springer, pp. 1–332. https://doi.org/10.1007/978-3-319-71486-8.

Schumann, F.R., 2020. Circular economy principles and small island tourism Guam's initiatives to transform from linear tourism to circular tourism. J. of Glob. Tour. Res. 5 (1), 13–20. https://doi.org/10.37020/jgtr.5.1.

Sciacca, A., 2020. *Circular economy transition in small island destinations*. Circular Conversations. https://www.circularconversations.com/research-series-young-researchers/circular-economy-transition-in-small-island-destinations. (Accessed 28 February 2023).

Singh, S.J., Elgie, A., Noll, D., Eckelman, M., 2023. The challenge of solid waste on small islands: proposing a socio-metabolic research (SMR) framework. Curr. Opin. Environ. Sustain. (in press).

Singh, S.J., Fischer-Kowalski, M., Chertow, M., 2020. The metabolism of islands. Sustainability 12 (22). https://doi.org/10.3390/su12229516.

Singh, S.J., Huang, T., Nagabhatla, N., Schweizer, P.-J., Eckelman, M., Verschuur, J., Soman, R., 2022. Socio-metabolic risk and tipping points on islands. Environ. Res. Lett. 17 (6), 065009 https://doi.org/10.1088/1748-9326/ac6f6c.

Tate, W.L., Bals, L., Bals, C., Foerstl, K., 2019. Seeing the forest and not the trees: learning from nature's circular economy. Resour. Conserv. Recycl. 149 (May), 115–129. https://doi.org/10.1016/j.resconrec.2019.05.023.

Ulanowicz, R.E., 2002. The balance between adaptability and adaptation. Biosystems 64 (1–3), 13–22. https://doi.org/10.1016/S0303-2647(01)00170-8.

Ulanowicz, R.E., 2009. The dual nature of ecosystem dynamics. Ecol. Model. 220 (16), 1886–1892. https://doi.org/10.1016/j.ecolmodel.2009.04.015.

Ulanowicz, R.E., 2020. Quantifying sustainable balance in ecosystem configurations. Curr. Res. Environ. Sustain. 1, 1–6. https://doi.org/10.1016/j.crsust.2019.09.001.

Ulanowicz, R.E., Goerner, S.J., Lietaer, B., Gomez, R., 2009. Quantifying sustainability: resilience, efficiency and the return of information theory. Ecol. Complex. 6 (1), 27–36. https://doi.org/10.1016/j.ecocom.2008.10.005.

UNEP, 2019. SIDS Waste Management Outlook. Available from: www.unenvironment.org. (Accessed 28 February 2023) https://www.unenvironment.org/ietc/node/44.

Walzberg, J., Lonca, G., Hanes, R.J., Eberle, A.L., Carpenter, A., Heath, G.A., 2021. Do we need a new sustainability assessment method for the circular economy? A critical literature review. Front. Sustain. 1 (January), 1–20. https://doi.org/10.3389/frsus.2020.620047.

Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists' warning on affluence. Nat. Commun. 11 (1), 1–10. https://doi.org/10.1038/s41467-020-16941-y.

Zisopoulos, F.K., Schraven, D.F.J., de Jong, M., 2022a. How robust is the circular economy in Europe? An ascendency analysis with Eurostat data between 2010 and 2018. Resour. Conserv. Recycl. 178, 106032 https://doi.org/10.1016/j.resconrec.2021.106032.

Zisopoulos, F.K., Teigiserova, D., Schraven, D., de Jong, M., Tong, X., Ulanowlcz, R.E., 2022b. Are there limits to robustness? Exploring tools from regenerative economics for a balanced transition towards a circular EU27. Clean. Prod. Lett. 3, 100014 https://doi.org/10.1016/j.clpl.2022.100014.

Zorach, A.C., Ulanowicz, R.E., 2003. Quantifying the complexity of flow networks: how many roles are there? Complexity 8 (3), 68–76. https://doi.org/10.1002/cplx.10075.