論文審査の結果の要旨

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Sustainability as a concept has multiple disparate perspectives stemming from different related disciplines which either maintain ambiguous interpretations or concentrate on metrics pertaining to single aspects of a system. Given the embedded multi-dimensionality of sustainability, systemic approaches are needed that can cope with interactions of different dimensions. While the concept of sustainability remains elusive, various attempts to construct a framework towards the quantification of sustainability have been made. However, most of these attempts can be classified as basic accounting approaches, and few holistic metrics that attempt to quantify intensive dimensions of sustainability, such as robustness, exist in the literature. Past efforts for measuring sustainability holistically have taken an accounting approach based on the availability and efficiency of resource flows. To date, these approaches often dissect sustainability into three dimensions: environmental, economic, and social dimensions. Quantitative indicators are then identified for each of the three dimensions separately or aggregated into a single numerical value. Yet, this approach leads to a fragmented assessment which treats sustainability dimensions as uncorrelated factors.

Therefore, an accounting approach fails to fully incorporate the intensive parameters pertaining to sustainability. An ecological information-based approach is a promising holistic measurement which incorporates both intensive and extensive dimensions of sustainability. This research begins with a critical review of attempts to apply the accounting methods of emergy, exergy, and ecological footprint, and the ecological information-based approach towards quantifying sustainable resource use. This research then evaluates this approach by applying it to 14 economic resource trade flow networks: virtual water, oil, world commodity, OECD+BRIC commodity, OECD+BRIC foreign direct investment, iron and steel, coffee, corn, wheat, sugar, natural gas, silver, gold, and cotton. These networks were selected because they represent economic resource networks with the highest traded value at the global scale, they are of high strategic economic importance, and/or they reflect environmental issues such as their scarcity.

The temporal trends of the system level measurements may convey information on the robustness of the network. However, without specific benchmarks pertaining to a particular network type, this information may not be of great benefit. Biomimicry offers one path for comparing heterogeneous network type and natural networks have been found to operate close to the maximum levels of system robustness. Deviations from this maximum can be used for planning

policy strategies. In this light, the findings for the socio-economic systems discussed in this research indicate that those networks are overly redundant. Therefore, to attain higher robustness, the efficiency of the examined economic resource networks needs to be increased. From the perspective of biomimicry, it appears that these networks can achieve higher levels of efficiency without weakening their robustness to resource delivery. However, mimicking the way that nature organizes its flow configuration is not an easy task. Natural systems are shaped by evolutionary dynamics which are forceful, cruel, and brutally effective. Achieving similar dynamism in a human socio-economic system may not be possible or desirable. Nevertheless, assuming that the mimicry of nature is beneficial, it is suggested that more robust delivery of economic resources can be achieved by balancing efficient delivery of resources with the ability of the system to withstand perturbations to its network structure.

A second avenue for finding an optimal level of robustness in a system is to follow a data-intensive approach. In this approach, a range of possible configurations for a network is measured whereby whilst a network remains in such a range, it is judged to be robust. This can be achieved by looking at many networks which share similar characteristics, for example economic resource networks, and mapping their configurations throughout time. Specifically, it is demonstrated how the ecological information-based network metrics of effective connectivity and effective number of roles can convey boundaries where economic resource networks are robust. Furthermore, it is demonstrated that actual human socio-economic networks show a pattern of commonality when viewed through the introduced metrics and that an intensive dimension of sustainability can be explained through a phenomenological rationale.

The research's original contribution to knowledge is threefold. Firstly, it conceptualizes the quantification of sustainability into two dimensions, namely an extensive dimension concerned with the availability of resource and an intensive dimension concerning the robustness of the system. Secondly, this research develops the first application of the ecological information-based approach to economic resource networks and advances the idea of biomimicry as a normative criteria towards the intensive dimension of sustainability quantification. Thirdly, this research explores and develops a data-intensive approach as an alternative normative criteria that may be used towards the quantification of sustainability. One of the main limitations within the field of sustainability science is the lack of a strong computational branch which is able to guide policy and decision making. It is hoped that this research serves as a contribution towards research in establishing a new direction in the quantification of sustainability.

This dissertation hereby has been approved for fulfilling the requirement for the degree of Ph.D. in Sustainability Science.

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