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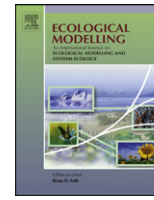

Comparative network analysis toward characterization of systemic organization for human–environmental sustainability

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ABSTRACT

A preliminary study in comparative ecological network analysis was conducted to identify key assumptions and methodological challenges, test initial hypotheses and explore systemic and network structural characteristics for environmentally sustainable ecosystems. A nitrogen network for the U.S. beef supply chain – a small sub-network of the industrial food system analyzed as a pilot study – was constructed and compared to four non-human carbon and nitrogen trophic networks for the Chesapeake Bay and the Florida Everglades. These non-human food webs served as sustainable reference systems. Contrary to the main original hypothesis, the "window of vitality" and the number of network roles did not clearly differentiate between a human sub-network and the more complete non-human networks. The effective trophic level of humans (a partial estimate of trophic level based on the single food source of beef) was much higher (8.1) than any non-human species (maximum of 4.88). Network connectance, entropy, total dependency coefficients, trophic efficiencies and the ascendency to capacity ratio also indicated differences that serve as hypotheses for future tests on more comprehensive human food webs. The study elucidated important issues related to (1) the steady state assumption, which is more problematic for industrial human systems, (2) the absence or dearth of data on contributions of dead humans and human wastes to feed other species in an integrated food web, (3) the ambiguity of defining some industrial compartments as living versus non-living, and (4) challenges with constructing compartments and trophic transfers in industrial versus non-human food webs. The two main novel results are (1) the progress made toward adapting ecological network analysis (ENA) methodology for analysis of human food networks in industrial cultures and (2) characterizing the critical aspects of comparative ENA for understanding potential causes of the problems, and providing avenues for solutions, for environmental sustainability. Based on this work, construction and comparative network analysis of a more comprehensive industrial human food network seems warranted and likely to provide valuable insights for modifying structures of industrial food networks to be more like natural networks and more sustainable.

1. Introduction

Comparing human ecosystems to non-human natural ones, many of which have persisted and self-perpetuated for tens of thousands of years, may help us discern if we can continue our current general human–environment relationship, if we need to make fundamental changes to achieve sustainability and what specific changes could improve our environmental relations and help solve problems (see for example Odum and Odum, 2001). Multiple sources of evidence suggest that current human activities result in a net detrimental impact such that environmental quality degrades over time. Example symptoms of this systemic dysfunction include increased extinctions and loss of biodiversity, changes in atmospheric composition and resulting climate destabilization, loss and degradation of soils, eutrophication of surface waters, and depletion of key energy sources, among other major problems. In contrast, non-human ecosystems appear to succeed where humans fail. The cumulative impacts of the activities of thousands to millions of species comprising forests, for example, serve to maintain and improve environmental quality and associated life support capacity over time. In forests, soils increase in amount and fertility, biodiversity is sustained despite fluctuations, renewable energy supplies are not depleted, and associated water and atmospheric capacities are not threatened.

This general contrast of non-human ecosystems as sustainable and human ecosystems as unsustainable is compatible with Daly's (1990) input–output rules for environmental sustainability, which require (1) use rates of non-renewable resources must be less than the rate at which renewable substitutes are developed, (2) use rates of renewable resources must be less than the regeneration rates by

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the natural system, and (3) emission rates for pollutants must be less than rates of recycling or decontamination of those pollutants.

The general question addressed here is: do network structural patterns differentiate between those systems that are environmentally sustainable and those that are not? A preliminary answer was sought by treating non-human ecosystems as environmentally sustainable reference cases and comparing ecological network topology between human and non-human trophic or food web networks. To address this question fully requires (1) a complete or comprehensive network of an industrial human food web, and (2) valid methods of ecological network analysis (ENA) compatible to both industrial human and non-human food webs. In this study, a very small sub-network of the human industrial food web was constructed and analyzed to identify conceptual and methodological challenges to extending ENA to industrial human networks. Several hypotheses were developed and tested in preliminary fashion to explore the potential of such an approach. Results of comparisons of network measures are presented in the context of an initial pilot study and thus are not to be interpreted as solely, directly or literally meaningful. Instead, the hypothetical and comparative differences between human and non-human food webs can serve as questions to be tested in the future once a more complete industrial human food network is constructed. The two main novel results of this project are (1) the progress made toward adapting ecological network analysis (ENA) methodology for analysis of human food networks in industrial cultures and (2) characterizing the critical aspects of comparative ENA for understanding potential causes of the problems, and providing avenues for solutions, for environmental sustainability.

Ecological network analysis (ENA) has been successfully developed and utilized for decades, mainly in reference to non-human ecosystems such as the Chesapeake Bay and Florida Everglades in the U.S. and other ecosystems worldwide (e.g., Baird and Ulanowicz, 1989; Ulanowicz et al., 1997; Fath and Killian, 2007). Based on hypothesized effects of large energy and nutrient subsidies in human ecosystems, the prediction was developed that human and natural ecosystems differ qualitatively in relation to the "window of vitality" (Ulanowicz, 2002a; Zorach and Ulanowicz, 2003). The window of vitality describes a narrow region bounded by two whole-network properties – the number of network roles (limited range of 2–4.5 in real ecosystems) and the effective connectance per node (limited range of 1–3.1). All real natural (and several human) networks analyzed thus far plot inside this window in parameter space. Networks with structure, nodes and links constructed randomly or via computer simulation are not so confined and can fall far outside this narrow region (Ulanowicz, 2002a). The human sub-network was predicted to exhibit more than 4.5 roles thus plotting outside the window of vitality. Zorach and Ulanowicz (2003) describe roles as "specialized functions" and propose the number of roles as a meaningful measure of network complexity. Ulanowicz (2004) also states that roles correspond roughly to the effective number of trophic levels or to the "trophic depth" of the network. If human food networks show more specialization, greater complexity and greater trophic depth than non-human networks, this could be an important indicator for defining and achieving sustainability.

The human food web studied was a sub-network within the U.S. food system. The beef supply chain, extending from farms and key farm inputs through human ingestion and on to waste disposal, was studied in terms of stocks and fluxes of nitrogen (N). The U.S. beef supply network possesses several key properties that should allow many results to be generally applicable to the industrial food system. Beef was chosen due to its status as the largest source of protein and N in the U.S. diet (USDA, 1998). The humans–beef network was deemed representative of major structural aspects of the U.S. food system, including agricultural production, food processing, long distance transportation, retail sales, home storage and preparation and wastewater treatment. The beef supply system also exhibits some of the basic carbon, nitrogen and energy characteristics of major environmental problems and efforts to define and achieve environmental sustainability.

In addition to testing the specific hypothesis regarding network differences and the window of vitality relevant to sustainability, six other network measures were compared. It is hoped that some of the methods, results and discussions will benefit sustainability science, aid action steps for sustainability and help solve the general, increasingly troublesome and apparently systemic problem of our current human–environment relation. The results also demonstrate the potential value of ecological network analysis and network models in general for framing and solving the systemic human–environment problem.

2. Data and methods

2.1. Construction of the human–beef supply network

Concise description of the dataset construction process for a representative sub-network of the human food web in the U.S. can be found in the online appendix. Additional details can be found in Fiscus (2007). In brief, a sub-network for a single food item was considered the best dataset for identifying challenges for comparing human to non-human networks. This simplification made it possible to trace fluxes all the way back to primary production. However, this choice posed challenges for comparing a single food pathway for beef to more complete networks in the non-human ecosystems. Also, while the human population studied was spatially bounded (see below), the beef supply chain was spatially dispersed over the entire U.S. This posed another conceptual difference when comparing to the more spatially bounded non-human ecosystems.

Two USDA nutrition datasets (USDA, 1998, 2006a) provided the top food items by average daily mass ingested. The 23 leading food items by mass ingested are listed in Table A1 (available in the online appendix) as ranked by protein amounts, as protein is the major source of nitrogen. From this data ground beef was ranked the top source of protein in 1994–1996. The beef supply network was developed based on an estimate of the beef ingestion of people in Allegany County, Maryland, a population of 75,000, for the year 2005. Annual beef consumption was taken as the U.S. average for 2005 of 23.2 kg per person (USDA, 2006a). From this starting point, beef production (and associated nitrogen fluxes) was traced back to an initial compartment of nitrogen fertilizer, and human wastes were traced forward to a final compartment of wastewater treatment. Compartmental standing stock units are kg N and flux units are kg N yr^{-1}. The network diagram is shown in Fig. 1, and the network matrix dataset and other data and references (Aillerry et

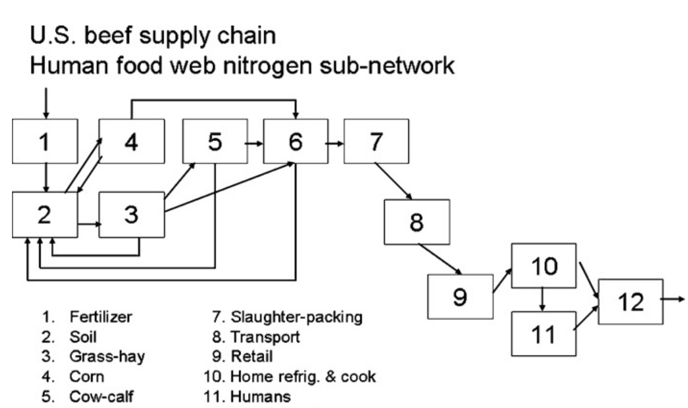

Fig. 1. Network diagram.