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

Daniel A. Fiscus *

Biology Department, Frostburg State University, 308 Compton Science Center, Frostburg, MD 21532, USA

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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

* Tel.: +1 301 687 4170; fax: +1 301 687 3034.
E-mail address: dafiscus@frostburg.edu.

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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

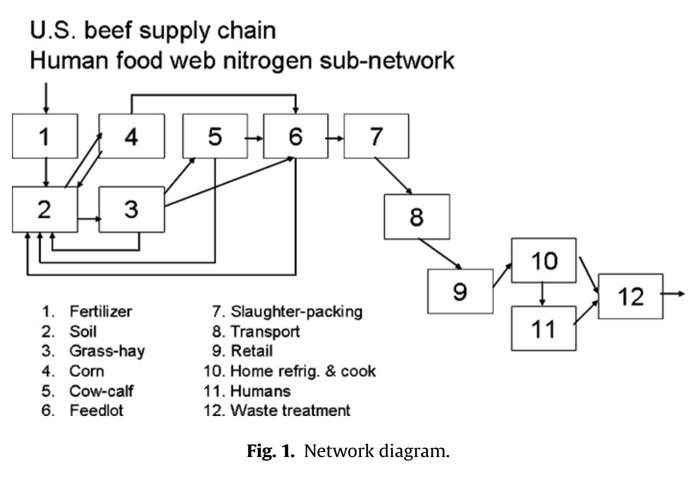

Fig. 1. Network diagram.

al., 2005; Bahar et al., 2005; Baker and Allen, 2006; Eghball et al., 1997; Ferguson et al., 2005; Gregory et al., 1994; Hao et al., 2005; Larney et al., 2006; NASS, 2006; Peterjohn and Correll, 1984; Pollan, 2006; Smil, 2002; Sterner and Elser, 2002; Tess and Kolstand, 2000; U.S. Census Bureau, 2006; USDA, 2006b; Vasconcelos et al., 2006) are in the online appendix.

The rationale for the compartments chosen and for comparing them to ecological organisms, species or compartments is based on several key assumptions. Addressing these assumptions poses a central challenge for meaningful comparisons between industrial human and non-human food webs. Like non-human ecological network participants, each of the human–beef supply compartments take in a food item or unit of nitrogen, transform or alter it in some way (e.g., slaughter a live animal, move beef from mid-west U.S. to mid-Atlantic U.S., etc.), and pass it on to another network actor. Also similar to non-human food webs, each compartment uses energy and causes fluxes of N and C in the transformation process it performs. This is analogous to metabolism, albeit a form of "industrial metabolism" that differs significantly from biological metabolism. The nitrogen and beef (and other foods) are not actually ingested in industrial compartments and are not transformed into another life form via true metabolism. Instead, the compartments defined and quantified in Fig. 1 are associated with distinct corporate and economic entities. Corporations form an economic boundary that enables tracking of energy and material fluxes via data reported, government statistics and similar information sources. This real economic identity was considered important for constructing the human network, but this difference with non-human networks requires further examination and consideration of alternative approaches. The approach taken results in a larger number of individual compartments, and also in a higher number of trophic levels, for the industrial food network. The dependence of these results on this choice of model construction is important for interpretation of the results.

While the compartments in Fig. 1 and for this study are specific to the beef supply chain, the general network structure seems applicable to many other major food items. With one or more generalized "agricultural production" components and additional generalized "food processing" components, very similar networks could be constructed for C, N or energy fluxes associated with chicken, turkey, pork, fish, milk, eggs, cheese, bread, pasta, pizza, oils, sugar, condiments, beverages and many other U.S. dietary staples. All of these foods would share functional components like the fertilizer, soil, crop plants and feed plants, transportation, retail, home refrigeration and cooking and wastewater treatment units developed for the beef N network.

2.2. Steady state assumptions

Several computations within ecological network analysis require an assumption of steady state conditions for the ecosystem of study. One must construct the network stocks and fluxes in such a way that inputs and outputs for each compartment and the network overall are balanced. Thus for the time interval of the study, the network and its compartmental stocks and fluxes are assumed neither growing nor declining significantly.

Unlike the living systems traditionally studied via ecological network analysis, industrial systems do not have standing stocks that are fully equivalent to living biomass. Also, the standing stocks that enable production are not equated easily with mainly abiotic ecological compartments like soils and detritus. Instead, standing stocks associated with the industrial beef supply chain are a blend of non-living mechanical equipment, living human workers and a variety of other building and infrastructure aspects. Examples of types of capacity that enable production in the slaughter and meat-packing compartment, and that contain or utilize N either directly or indirectly, are (1) buildings with associated heating, cooling and lighting, (2) large machinery like conveyors and refrigeration, (3) energy supplies including fossil fuels, electricity, coal, gasoline and natural gas, (4) small equipment like knives, brooms, hoses, (5) vehicles and (6) human workers.

Also unlike living systems, industrial systems do not directly regenerate their own capacity for production with each work cycle. That is, there is not an onsite (nor even corporate or national) allocation of energy or nutrients that serves to replenish and sustain the infrastructure in the same way that organisms allocate energy and nutrients to replenish and sustain living tissues and ecosystem organization achieves maintenance, regeneration and enhancement of soils and biodiversity. Thus at the environmental, ecosystem, national and global levels the steady state assumption of no decrease in essential productive standing stocks is not fully valid for U.S. industrial systems, since some of these stocks are in fact declining significantly due in part to the impacts of industrial agriculture (Campbell, 2005; Tilman et al., 2002).

Without fully resolving these issues, this project served to identify and begin to characterize them. The N fluxes for human workers in the supply chain were ignored, and it was assumed that stocks of productive capacity would somehow be replaced as for a steady state network (see more on this in Section 4). The simple aspect most similar for industrial and ecological networks is the mass of beef always present in each compartment of beef supply network. This was used to estimate standing stocks of N in beef in the industrial compartments.

2.3. Non-human datasets for comparisons

Three datasets for the Chesapeake Bay mesohaline ecosystem were used for comparison to the U.S. humans and beef network. The full Chesapeake Bay carbon (C) dataset (Baird and Ulanowicz, 1989) depicts the summer season and has 36 compartments of which 3 are non-living. Its units are mg C/m^2 for biomasses and stocks and mg C/m^2/summer for fluxes. A full Chesapeake Bay nitrogen dataset (Ulanowicz and Baird, 1999) had the same compartments but in units of mg N/m^2 for biomasses and stocks and mg N/m^2/summer for fluxes. An aggregated dataset in which the full C network was compressed into 12 living and 3 non-living compartments was also analyzed (Wulff and Ulanowicz, 1989), since it is closer in number of compartments to the humans–beef network. Bluefish was the main species used for comparisons to humans. In addition to being a top predator, bluefish provide a good comparison since they also gain food over very long trophic path lengths.

A fourth dataset used for comparisons was for the Florida Everglades cypress swamp ecosystem (Ulanowicz et al., 1997). This dataset characterizes feeding relations in the Everglades wet season (May through October) and has 68 compartments of which 65 are living. Units are g C/m^2 for biomasses and stocks and g C/m^2/yr for fluxes. Within the Everglades ecosystem, humans were compared to alligators, black bears and Florida panthers. All three are top predators and alligators especially have a large number of prey and diet items and feed over long path lengths.

2.4. Ecological network analysis theory and techniques

Ecological network analysis (ENA) was employed to test the hypotheses and explore the relationship of ecosystem network organization to environmental sustainability. As developed by Ulanowicz (1986, 1997, 2002b, 2004), ENA comprises a set of analytical tools and computer algorithms for understanding the holistic and non-mechanistic nature of ecosystems. Central to the underlying theory for ENA is the view that communities and ecosystems have interdependent, relational aspects that are not understandable via focus on parts of the network in isolation. Ulanowicz (1999)

Table 1
Comparisons of network information indices, connectance and roles.

Network Atttribute	Chesapeake Bay full C	Chesapeake Bay full N	Ches. Bay Aggregated C	Florida Everglades C	Humans and beef N	Human versus others
Information indices						
TST[a]	4.12E+06	5.58E+05	1.12E+04	3.99E+03	1.88E+07	
Capacity (C)	1.97E+07	2.69E+06	5.02E+04	1.96E+04	6.64E+07	
Ascendency (A)	8.59E+06	1.15E+06	1.63E+04	6.58E+03	3.42E+07	
AMI[b]	2.088	2.061	1.456	1.649	1.815	
Entropy (*H*)	4.775	4.821	4.470	4.918	3.527	Low
A/C	0.437	0.427	0.326	0.335	0.515	High
AMI/*H*	0.437	0.427	0.326	0.335	0.515	
Redundancy (R)	5.71E+06	1.14E+06	1.85E+04	5.05E+03	1.67E+07	
Internal C	1.16E+07	2.05E+06	2.85E+04	7.13E+03	3.23E+07	
Internal A	5.87E+06	9.14E+05	9.97E+03	2.09E+03	1.56E+07	
Int A/Int C	0.507	0.446	0.350	0.293	0.482	
R/Int C	0.493	0.554	0.650	0.707	0.518	
Int A/A	0.683	0.796	0.610	0.317	0.456	
Total overhead (O)	1.11E+07	1.54E+06	3.38E+04	1.30E+04	3.22E+07	
O for imports	1.70E+06	1.12E+05	4.72E+03	3.89E+03	7.62E+06	
O for exports	7.97E+04	2.62E+05	4.02E+02	2.86E+02	6.17E+06	
O for dissipation	3.57E+06	3.12E+04	1.02E+04	3.82E+03	1.68E+06	
O imp./C	0.087	0.042	0.094	0.198	0.115	
O exp./C	0.004	0.097	0.008	0.015	0.093	
O diss./C	0.181	0.012	0.203	0.195	0.025	
R/C	0.291	0.422	0.370	0.257	0.252	Low
Connectance measures						
Overall	2.036	2.679	2.395	1.852	1.754	Low
Intercom-partmental	1.95	2.286	2.268	3.256	1.762	Low
Foodweb	1.754	1.828	1.87	2.019	1.196	Low
Network roles						
No. roles	4.25	4.17	2.74	3.14	3.52	

[a] TST is total system throughput.
[b] AMI is average mutual information.

elaborates this view in his "ecological metaphysic" and promises improvement for mainstream life sciences now based on mechanistic and Darwinian philosophical foundations (Ulanowicz, 2009).

The pragmatic tools of ENA involve identification and quantification of stocks and fluxes of key ecological "currencies" such as energy, carbon, nitrogen, and phosphorus but can also be applied to any currency that is exchanged in a network. Compared to dynamic modeling, the network approach is often atemporal – the organizational relations of stocks and fluxes are studied for a snapshot in time during which they are treated as unchanging. This atemporal aspect can provide a complementary perspective to dynamic modeling.

Ecological network analysis was conducted in comparative fashion to elucidate similarities and differences in the network organization of a partial human food web relative to several non-human natural ecosystems. From among the many ENA tools seven metrics were chosen based on their relevance to sustainability and potential for showing pivotal similarities and differences between human and natural systems. The comparative network approaches employed were: (1) effective trophic levels and trophic efficiencies (Ulanowicz, 1995, 2002b; Ulanowicz and Kemp, 1979); (2) degree and structure of material cycling (Ulanowicz, 1997, 2002b); (3) information indices including ascendency, overhead and capacity (Ulanowicz, 2002b, 2004); (4) connectance (EcoNetwrk, 2007); (5) number of roles and the "window of vitality" (Ulanowicz, 2002a; Zorach and Ulanowicz, 2003); (6) residence times (Ulanowicz and Baird, 1999; Fath et al., 2001); and (7) total contributions and dependencies (Ulanowicz, 2002b). As defined in Zorach and Ulanowicz (2003), the number of network roles is calculated as 2 raised to the average mutual information (AMI) power.

The software utilized for these analyses included Netwrk 4.2b (Ulanowicz, 2002b) and EcoNetwrk (EcoNetwrk, 2007), both of which use the same core algorithms. Each of the metrics and the comparison methods are described in more detail in Fiscus (2007). This software requires assignment of living and non-living compartments. The beef supply network was defined with nine living and three non-living compartments (fertilizer, soil and wastewater treatment plant). The definitions as living compartments for feedlots, slaughter and meatpacking, transportation, retail and home refrigeration and cooking are arguable. The rationale was that these compartments are more like living systems that actively transform or impact, and then pass on a food item, than they are like non-living detrital or abiotic pools in which transformation is more passive and does not have an associated metabolism or respiration. This imperfect assignment and assumption affects the results in that the ENA software used treats living and non-living compartments differently. This affects the trophic analysis and calculation of effective trophic levels most directly, as non-living compartments are all lumped together in a single detrital trophic level (Ulanowicz, 2002b). These issues suggest another area for examination of the extension of ecological network analysis to human and industrial systems, and they are addressed more in Section 4.

Table 2
Comparison of network cycling.

Cycling attribute	Chesapeake Bay full C	Chesapeake Bay full N	Ches. Bay aggregated C	Florida Everglades C	Humans and beef N
Cycling index	0.212	0.526	0.305	0.059	0.250
Number of cycles	62	52,788	20	3,966,554	6
Longest cycle path length	6	17	4	18	4

Table 3
Effective trophic levels.

Chesapeake Bay full			Ches. Bay aggregated		Florida Everglades		Humans and beef	
Species	Effective trophic level (C)	Effective trophic level (N)	Species	Effective trophic level (C)	Species	Effective trophic level (C)	Compartment	Effective trophic level (N)
Bluefish	4.53	4.88	Carnivorous fish	3.16	Alligator	3.78	Humans	8.1
Croaker	4.00	4.00	Benthic invert. carn.	2.81	Snakes	3.75	Home-rc	7.1
Catfish	4.00	4.00	Deposit feeders	2.00	Woodstork	3.43	Retail	6.1
Spot	3.99	4.02			Owls	3.33	Transport	5.1
Summer flounder	3.99	4.74			Kites/hawks	3.33	Slaughter	4.1
White perch	3.99	4.07			Florida panther	3.30	Feedlot	3.1
Hogchoker	3.89	3.98			Bobcat	3.04	Cow-calf	3.0
Striped bass	3.86	4.61			Turtles	2.82	Grass–hay	2.0
Blue crab	3.50	3.82			Black bear	2.25	Corn	2.0
Bay anchovy	2.84	3.64			Crayfish	2.25	Fertilizer	1.0
Menhaden	2.77	3.50			Terrestrial ins.	2.00	Soil	1.0
Zooplankton	2.16	2.93			Understory	1.00	WWTP	1.0
Phytoplankton	1.00	2.00			Phytoplankton	1.00		

3. Results

The dataset for the beef supply chain as a sub-network of N flux in the U.S. human food web is presented in diagram form in Fig. 1 and matrix form in Table A2 (available in the online appendix). Fig. 1 shows only internal flow links, but Table A2 includes the quantities of N in imports, exports, respirations and standing stocks associated with each compartment. As mentioned in the introduction, the following results are presented in the context of a preliminary pilot study to identify key methodological issues. Given that the human network analyzed was a very small sub-network of the larger human trophic network, numerical comparisons to the non-human ecosystems are more useful as initial hypotheses than comparisons in and of themselves.

It is interesting to note the difference in topology and especially recycling links between the agricultural and ecological first half of the network and the industrial, commercial, residential, human and municipal second half. In the latter, from slaughter and meatpacking through wastewater treatment, all flows are linear and no recycling occurs. As discussed in the methods of Fiscus (2007) this would change somewhat if fuller accounting were done, such as including flux of N in biosolids applied to farmland nationally.

Using the values for average mutual information (AMI) for each network, the number of network roles was calculated (see Table 1). The value for the human–beef network (3.52 roles) was intermediate between the higher values in the full Chesapeake Bay C and N networks (4.25 and 4.17 respectively) and the lower values in the aggregated Chesapeake Bay C and Everglades C networks (2.74 and 3.14). The pair of values for overall connectance (1.75) and network roles (3.52) indicated that the human–beef network plotted inside the window of vitality contrary to the original prediction.

Table 2 reports results for the number of distinct material cycle pathways, proportion of total throughput that is recycled (Finn cycling index) and longest cycle path lengths for each of the five networks. The human–beef sub-network was most similar to the Chesapeake Bay aggregated C network for longest cycle path lengths and proportion of material cycled. Compared to the other C networks, the human N network showed a greater proportion of cycled flow (25%) but over fewer pathways and shorter path lengths. Compared to the full Chesapeake N network (53% recycled flow), the human–beef supply chain had less than half the proportion of recycle flow and again over far fewer cycles and far shorter longest path lengths.

The effective carbon network trophic levels of bluefish (4.53), carnivorous fish (3.16), alligators (3.78), Florida panthers (3.3) and black bears (2.25) were all far less than the effective nitrogen trophic level of humans in the human–beef sub-network (8.1). Effective trophic levels reported in Table 3 show bluefish in the N network (4.88) to be the highest of any of the non-human species studied. The very high trophic level for humans is influenced by the decision to treat many hybrid human-industrial compartments such as slaughter and meatpacking, transportation, retail and home refrigeration and cooking as living compartments during network analysis.

Comparison of trophic efficiencies showed that the human–beef supply chain is quite different than the natural C and N networks examined. Trophic efficiency is the ratio of the input to a trophic level to the amount that trophic level passes on to the next (Ulanowicz, 2002b). Whereas natural networks usually show highest trophic efficiencies in the first one or two trophic levels with strongly declining efficiencies going up the food chain, the human–beef network has extremely high efficiencies in upper levels of the slaughter and meat-packing, transportation, retail and

Table 4
Comparison of network trophic or transfer efficiencies.

Trophic efficiencies					
Trophic level	Chesapeake Bay full C	Chesapeake Bay full N	Ches. Bay aggregated C	Florida Everglades C	Humans and beef N
1	0.792	0.766	0.520	0.244	0.290
2	0.351	0.303	0.183	0.026	0.541
3	0.110	0.194	0.072	0.083	0.104
4	0.114	0.133	0.070	0.153	0.682
5	0.085	0.106	0.012	0.066	0.983
6	0.034	0.085		0.028	0.986
7	0.008	0.008		0.015	0.908
8				0.005	0.095
9				0.002	
10				0.001	

home refrigeration and cooking compartments, each of which acts as its own trophic level (Table 4). These "industrial trophic efficiencies" would be only slightly lower with N fluxes associated with energy use and NOx emissions included, since these fossil fuel-based fluxes of N are likely much less than the fluxes of N in beef. Comparisons of trophic levels for carbon and nitrogen networks in the Chesapeake Bay showed very similar efficiencies at all levels.

Results for many comparisons of information indices are in Table 1. One of the most interesting results is the relatively high ratio of ascendency to capacity for the human–beef network. This ratio value of 0.51 exceeded the 0.43 value for the full Chesapeake Bay C network, the highest of the non-human ecosystems. Corresponding to this was the lower network developmental capacity of the human–beef N network (3.53), notably less than the non-human C and N networks (range of 4.47–4.92). Capacity (or network developmental capacity) is the sum of ascendency and overhead (Ulanowicz, 2004) and thus represents the total of both organized, constrained and efficient structure (as indicated by ascendency) and unorganized, unconstrained and inefficient (overhead) structure in a system of network flows. Regarding the ratio of ascendency to capacity, Ulanowicz (2004) notes that systems with a high degree of ascendency relative to overhead appear to be rigidly linked, mechanical and thus vulnerable to collapse.

Comparisons for overhead measures also showed differences. Overhead is a measure of unorganized network flows and it increases due to four factors – uncertainty about (1) imports, (2) exports and (3) dissipations (respirations), and (4) flows proceeding along parallel pathways (i.e., structural redundancy) (Ulanowicz, 2002b). Ulanowicz (2004) suggests that freedom to adapt to novel perturbations is contained in the system overhead, and that a "healthy" ecosystem, or one with biotic "integrity", requires adequate amounts of both ascendency and overhead.

The proportion of capacity expressed as redundancy was slightly lower for the human–beef network (0.25) than the non-human networks (range of 0.26–0.42). The human–beef network also had a higher proportion of capacity in overhead for exports compared to the C networks but was similar to the Chesapeake Bay N network. Likewise, the proportional overhead for dissipation was lower for the human–beef network than for the C networks but more than that found for the Chesapeake Bay N network.

For several information indices including average mutual information (AMI), the internal ascendency to internal capacity ratio, the redundancy to internal capacity ratio, internal ascendency to total ascendency ratio, and proportional overhead on imports, the human–beef network was comparable to or not clearly different from the non-human networks. Some of the measures are not directly comparable (e.g., total system throughput, ascendency, capacity, redundancy) as they represent very different units. The ratios above provide a means for comparison given different network dataset units.

For all three of the connectance measures the human–beef network showed lower values than the non-human networks (see Table 1). Overall connectance was 1.75 links per node compared to a range of 1.85–2.68 in the Chesapeake Bay and Everglades systems. Intercompartmental and food web connectance were similarly lower.

Residence times for N and C in all the human–beef compartments and several important compartments in the Chesapeake Bay and Everglades ecosystems are not shown but are in Fiscus (2007). Residence times for N in the human–beef network ranged from 0.0005 years (about 4 h) in the slaughter and meatpacking unit to over 24 years in the soil compartment. Residence times in all the industrial compartments were much less than for the ecological compartments. Residence times generally increased with increasing trophic level with times for grass, hay and corn ranging from 20 to 100 days, cow-calf and feedlot around 50 days and humans

Table 5
Dependency coefficients. Proportion of total ingestion by focal species that passes through other species or compartments. LT: link type; D: direct; I: indirect.

Chesapeake Bay full C			Florida Everglades C									Humans and beef N		
Bluefish			Alligator			Black bear			Florida panther			Humans		
Species or Cpt.	Depend.	LT	Species or Cpt.	Depend.	LT	Species or Cpt.	Depend.	LT	Species or Cpt.	Depend.	LT	Species or Cpt.	Depend.	LT
Suspended POC	0.741	I	Fish HO	0.546	D	Understory	0.462	D	Deer	0.439	D	Home-rc	1.000	D
SPOT	0.609	D	Labile detritus	0.398	I	Hardwood L	0.437	D	Understory	0.412	I	Retail	1.000	I
Bacteria in sed. POC	0.586	I	Periphyton	0.302	I	Terrest. insects	0.120	D	Hardwood L	0.388	I	Transport	1.000	I
Sediment POC	0.586	I	Aquatic insects	0.247	D	Labile detritus	0.043	I	Hogs	0.230	D	Slaughter	1.000	I
Phytoplankton	0.511	I	Phytoplankton	0.205	I	Periphyton	0.022	I	Raccoon	0.200	D	Feedlot	1.000	I
Other Polychaetes	0.441	I	Macrophytes	0.151	I	Fish HO	0.021	I	Terrest. insects	0.181	I	Soil	0.930	I
Zooplankton	0.329	I	Living POC	0.147	I	Cypress L	0.021	I	Armadillo	0.095	D	Corn	0.718	I
Bay anchovy	0.225	D	Living SED	0.143	I	Deer	0.020	D	Labile Det.	0.093	I	Grass–hay	0.525	I
Menhaden	0.192	D	Crayfish	0.127	D	Rabbits	0.020	D	Periphyton	0.056	I	Fertilizer	0.305	I
Nereis	0.146	I	Prawn	0.105	D	Hogs	0.020	D	Crayfish	0.049	I	Cow–calf	0.303	I
Ciliates	0.110	I	Float Veg.	0.099	I	Vert. det	0.017	I	Cypress L	0.036	I			
Macoma spp.	0.098	I	Turtles	0.094	D									
Free bacteria	0.081	I	Snakes	0.091	D									
DOC	0.081	I	Terrst. Insects	0.090	D									
Benthic diatoms	0.070	I	Refractory detritus	0.087	I									
Hetero. microflag.	0.067	I	Fish PC	0.085	D									
Meiofauna	0.043	I	Cypress L	0.084	I									
Bacteria in sus. POC	0.035	I	Salamanders	0.070	D									
Ctenophores	0.014	I	Understory	0.048	I									
			L Fish	0.044	D									

around 80 days. It is interesting to note that beef (in the form of live animals) spends about 6 months in the cow-calf and feedlot operations (see below), but during and after slaughter and conversion to a food product beef then spends about a day in each of the industrial compartments.

Residence times for N in the Chesapeake Bay species ranged from about 18 h for phytoplankton to about 14 days for catfish. Residence time for N in bluefish was about 8 days. Residence times for C in Everglades species ranged from about 6 h for phytoplankton to 168 days for understory plants. Times for C in alligators, Florida panthers and black bears were 55, 25 and 25 days respectively.

The total contributions into a set of example species are reported in Fiscus (2007). The values tell what percent of all the production leaving a given compartment eventually enters bluefish, alligators, black bears, Florida panthers and humans over all pathways, direct and indirect. Also noted is whether these contributions come via direct or indirect pathways. The human–beef network shows similar patterns as natural systems in that the highest contributions come from direct prey or transferring compartments, these contributions decline with indirect transfers, but some small proportional contributions extend to many other participants and distant nodes in the networks.

Total contribution coefficients can also be quantified in the opposite direction. These measures indicate what percent of all the production leaving bluefish, alligators, black bears and Florida panthers eventually reach other compartments over all pathways, direct and indirect. These coefficients were not estimated for humans as no recycling or forward contributions of N via human waste or mortality were quantified in the human–beef network. For the non-human species, total contribution coefficients indicate the guild of species that decompose each of the focal species, thus making the nutrients embodied in them and in their wastes available for future employment in the ecosystem. As shown in Fiscus (2007), the ranking of relative contributions is identical for alligators, Florida panthers and black bears through seven compartments. All have the same ordering of contributions to vertebrate detritus, labile detritus, living sediment, refractory detritus, terrestrial insects, living particulate organic carbon, and opossum. The ranked contributions then vary, but all include vultures, crayfish, lizards and alligators. Despite the lack of quantitative results for humans, this experience from the network construction, analysis and total contribution coefficients has important implications that are discussed further below.

Total dependency coefficients are listed in Table 5. These measures indicate the fraction of total N or C ingestion by bluefish, humans and the other focal species that passed through each of the other compartments over all direct and indirect pathways. The link types (direct or indirect) are indicated. Unlike for contributions, these need not have highest values for direct links, and for bluefish the highest dependency is associated with an indirectly linked compartment. The highest dependencies for humans in the beef supply chain are anomalous in that no other species exhibit total dependencies of 1 (i.e., 100%) like humans do for N in beef passing through the feedlot, slaughter and meatpacking, transport, retail and home refrigeration and cooking mediating steps. While these results are somewhat artificial in that the network dataset did not include estimates of likely small N dietary fluxes from food obtained from local farms or farmers markets, they would not likely change much for the majority of U.S. and Allegany County citizens even with this additional level of detail.

4. Discussion and conclusions

This report presented results of comparative network analyses for human and non-human ecosystems toward understanding the causes of major environmental problems and organizational principles for human–environmental sustainability. The main hypothesis for a distinguishing feature for sustainable versus unsustainable systems was the number of network roles as associated with the window of vitality or WOV (Ulanowicz, 2002a). The industrial human ecosystem network was predicted to exhibit greater than 4.5 roles and thus plot outside the WOV. No natural ecosystem of the nearly 50 analyzed so far (which includes one human economic network) has ever been observed to plot outside this narrow region of network configuration space (Ulanowicz, 2002a). Contrary to the main prediction, the humans–beef N network plotted inside the WOV region and was found to have 3.5 network roles and 1.8 effective connections per node. The number of roles was less than the C and N networks for the full Chesapeake Bay networks, and more than the aggregated Chesapeake Bay and Florida Everglades C networks. The original prediction was based on (1) the hypothesis that trophic levels would be abnormally high for human food webs due to effects of energy and nutrient subsidies and (2) an assumption that network roles and effective trophic levels are synonymous or closely correlated. The humans–beef N network exhibited a maximum effective trophic level of 8.1 for humans (a partial trophic level, based on beef only), and this exceeds natural food webs for which an effective trophic level limit of about 5 has been widely observed (though its cause is not agreed upon (Post, 2002)). However, as shown here, network roles and effective trophic levels are not the same or necessarily varying together for the case of the industrial humans–beef network.

This result suggests the comparative network analysis employed here does not enable the window of vitality to provide a clear indicator of environmental sustainability. It seems that the four highly linear industrial and residential network compartments – slaughter and meatpacking, transportation, retail and home refrigeration and cooking – may be so similar and simple as to collapse into a single network role. Additional data and fuller accounting for inputs, outputs, imports and exports for these compartments might lead to different results including a higher number of roles in this subnetwork. Humans did eat at a higher effective trophic level (8.1) than any other species (maximum of 4.88). Thus effective trophic level of the top carnivore is the more clear indicator of a sustainable ecosystem network based on this work.

Some analyses within ENA require an assumption of steady state network conditions in which stocks and fluxes are not increasing or decreasing significantly. This assumption can be made without serious conceptual problems for study of natural ecosystems when a relatively short time span of one or a few years is adopted, and it can even be trusted to hold true over long time frames in a general sense. This assumption is valid largely because living ecosystems are self-sustaining and self-regenerating. This same assumption of steady state conditions is problematic for human systems such as the industrial U.S., however. Our overwhelmingly dominant energy source is fossil fuels, and as we utilize this finite and non-renewable resource it declines in direct proportion to our use. Many energy analysts now predict that the world has reached or will soon reach the peak of oil production (e.g., Campbell, 2005) and that supplies will soon begin to decline. Thus unlike the long-term applicability for steady state ENA to natural systems that extends billions of years into the future, we have perhaps on the order 10 or at most 100 years before a crucial capacity factor for the operation of U.S. human and industrial systems can no longer reasonably be treated as stable and non-decreasing.

This steady state assumption problem was not resolved in the present study, as the imports, exports and respirations of energy, nitrogen and carbon associated with fossil fuels were not directly quantified and analyzed in relation to beef production and consumption. One option would be to add a fictitious compartment to the network that accounts for the real decline in non-renewable fossil fuel capacity and balances that depletion via hypothetical creation of new energy capacity. The amount of capacity lost during the time span of the network analysis would be recorded in this fictional compartment, and this would serve to quantify the debt in “natural capital” or real environmental capacity accrued during the period of study.

The humans–beef nitrogen network had a higher proportion of total network flux as recycled flux (25%) than any of the non-human carbon networks examined. The Chesapeake Bay full network for N, however, had more than twice the proportion of recycling (53%). The N recycling in the humans–beef network also occurred over relatively short path lengths (number of links), mainly via manure applications from feedlots and cow-calf operations to soils and litter inputs from corn, grass and hay. This combination of a large amount of recycling over short path lengths has been associated with eutrophic and disturbed ecosystems such as the Chesapeake Bay that receive excess N inputs from human-dominated landscapes (Ulanowicz, 1997). One similarity that suggests this a valid correspondence is that the beef supply chain is also heavily subsidized with N inputs via fertilizer use. Nearly 10 times as much N subsidy flowed as fertilizer applied for cattle feed (700,000 kg/yr) as N eventually ingested in beef by humans (75,871 kg/yr). Bleken and Bakken (1997) also reported that edible products actually ingested account for about 10% of total N inputs to plant crops in Norway's food system. Steinhart and Steinhart (1974) also found that the energy input per calorie of food energy output increased from about 1 to about 10 between 1910 and 1970.

Other results include a greater ascendancy to capacity ratio for the humans–beef network than any non-human network. This result could be generalized to an observation that this example sub-network shows how heavily the U.S. system has been pushed toward efficiency, ostensibly as driven largely by economic competition. The trophic or transfer efficiencies for the industrial and commercial transportation, retail, home refrigeration and cooking compartments were all much higher (range 0.91–0.99) than any non-human trophic efficiency observed (highest of 0.79 in the first trophic level of the full Chesapeake Bay C network). Lower residence times observed in the industrial compartments relative to the agricultural and ecological compartments reflect this economic influence as well. As mentioned, these N-transfer efficiencies likely would be only slightly lower if measures of N fluxes associated with fossil fuel use and human workers were included, as these external fluxes are much less than the mass of N in beef moving through these compartments. However, the validity of comparisons of such “industrial trophic efficiencies” and true trophic efficiencies requires further examination.

High efficiency, while good for reducing losses of valuable meat along the supply chain, also appears to be associated with a loss of reliability and redundancy. Comparisons of total dependency coefficients showed humans to be the only species with total dependency (coefficients of 1) on any compartment. The humans–beef N network, as limited as it is in scope and coverage of the highly diverse U.S. diet, in fact showed total dependency (100% of beef ingested was mediated by other compartments) on five different compartments in the highly linear beef supply chain – feedlots, slaughter and meatpacking, transportation, retail, and home refrigeration and cooking. This dependency factor would decrease if fuller accounting were made of local and alternative sources of meat and protein, such as from farmers markets, local farms, personal gardens and hunting. But these decreases would also likely be offset by additional dependencies on the same or similar industrial food system compartments, since many other staple foods like chicken, turkey, beans, bread, eggs, milk and others are grown, processed, transported, supplied via supermarket and stored and prepared at home in much the same ways.

Three measures of network connectance were lower for the humans–beef network than any non-human network. Overall, intercompartmental and foodweb connectance were all reduced relative to Chesapeake Bay and Florida Everglades. These differences might decrease somewhat if additional fluxes known to exist in the humans–beef supply network were included, such as additional local pathways for foods, pharmaceuticals and supplements in cattle feed, and others. But fewer connections per node also is compatible with inspection of network diagrams, the high number effective trophic levels given the relatively low number of total compartments and the high trophic or transfer efficiencies. As mentioned above, 90–99% transfer efficiencies are perhaps only possible via a highly linear supply chain in which the vast majority of flux is channeled along very few links.

Comparisons to focal species like bluefish in the Chesapeake Bay and Florida panthers, black bears and alligators in the Everglades provided interesting and evocative results. One of these was seen in the total contribution coefficients going out or forward from each focal species via fluxes associated with death and waste egestion. These fractions of production that become inputs to other species could not be calculated for humans in the humans–beef network, as no fluxes were quantified by which dead human bodies or human wastes were ingested by other species. The list of carrion feeders and decomposers that receive the dead bodies and wastes of the fish, bear, panther and alligator species brings to light that we humans do not typically consider – in a positive way! – how we can in fact become food for other species.

Differences in statistical entropy values (H) between human and other networks were also intriguing. The humans–beef H value (3.5) was lower than the other networks, which varied only slightly amongst themselves (range of 4.5–4.9). How H relates to species diversity, functional diversity, system developmental capacity, trophic levels, network roles and the window of vitality all seem fruitful to explore. As defined in Ulanowicz (2002b, 2004), H is an upper bound on average mutual information (AMI), and the number of network roles is calculated as 2 raised to the AMI power. If AMI is typically observed in a narrow range such as 30% to 50% of H it may be that H is ultimately responsible for the observed limit of 4.5 roles in all networks.

The human food web, in the example of the beef supply sub-network, shows signs of the strong role played by economic, industrial, technological and mechanical factors unique to human ecosystems. The temptation to increase efficiency in any given compartment is similar to the natural tendency of ecosystems to increase in ascendency, a whole-system measure of coherency, organization and orderliness of network stocks, fluxes and links. But in natural ecosystems ascendency is always in dynamic tension with system overhead, that complementary portion of total system developmental capacity than is unorganized, redundant and less efficient (Ulanowicz, 1997). The humans–beef network had a higher ascendency to capacity ratio than any of the other networks studied. If we push this ratio beyond normal or natural limits, as if we have no need for any redundant or parallel pathways to provide reliability and resilience to changing conditions, we may find our food supply system encounters trouble in the form of disruption and reduced food security. Combined with the known problems of resource depletion and excess waste emission, this potential organizational and network problem provides both cause for concern and basis to inform strategy and direction for concerted efforts to increase the sustainability of the U.S. food supply network and human society in general.

While ENA has been performed on a wide variety of non-human ecosystems, it has rarely been used to examine human and coupled human-natural systems for ecosystem currencies such as energy, carbon and nitrogen. Two examples of ENA that do address human systems include a study of the human N network in the food system of Norway (Bleken and Bakken, 1997) and money flows in the Polish economy (Szyrmer, unpublished data; Ulanowicz, 1986). Ecological network studies comparing human and non-human food webs may reveal time-tested, successful and robust organizing principles that we can use as role models and "technology transfer" like that developed in the fields of biomimicry (Benyus, 2002), permaculture (Mollison, 1996) and ecological engineering (Kangas, 2004). The window of vitality and the number of network roles did not clearly indicate the U.S. beef supply network to be unsustainable as in abnormal compared to non-human food webs. These two measures may show differences based on analysis of a more complete human food web. The effective (partial) trophic level of humans compared to other top carnivores, network connectance, entropy, total dependency coefficients, trophic efficiencies and the ascendency to capacity ratio did indicate differences that may be useful for modifying the network structure of the beef supply and similar industrial food supply systems to be more sustainable. The comparative ENA process itself also elucidated important issues related to (1) the steady state assumption, which is problematic for industrial human systems, (2) the absence or dearth of contributions of dead humans and human wastes to feed other species in an integrated food web, and (3) the ambiguity of defining some industrial compartments as living versus non-living. Addressing these issues of methodology and data should improve the ability of ENA to provide indicators of sustainability by allowing more valid comparisons to non-human reference ecosystems.

According to many observers, it appears likely that we face a turning point in our relationship to our natural environment. Odum and Odum (2001), a famous ecological science couple, forecast a downward trend in human energy use in the U.S. and other industrial societies and interpreted this trend the following way:

> There is no modern experience in coming down to go by, but we do have some principles about cycles. . .and the historical record of past civilizations. . .We get some ideas observing ecosystems when they contract.

As mentioned in this quote, comparative ecosystem studies could help us understand long-term environmental trends and key relationships. We now have many ecological network analysis tools available, and the opportunity to study successful, living network models of sustainable natural ecosystems. The process of "coming down" mentioned above could mean reducing the effective trophic level at which humans feed – we in the U.S. may eat three levels beyond a limit in non-human food webs of about five trophic levels. For a human ecosystem to "contract", as mentioned above, could be interpreted to suggest not only reducing the number of processing steps in our food supply networks, but also to consider more explicitly "completing the cycle" in materials loops such that human wastes, and even our bodies after death, become food for other species in beneficial, mutualistic ways. We might ask, how do we feed ourselves within a larger ecological network such that the whole process of bringing humans into material existence can be sustained over the long-term? Guidance may be found by comparison to the ways natural community-ecosystems have done this so well, for so many species, for so long.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2009.05.006.

References

Aillerry, M., Gollehon, N., Johansson, R., Kaplan, J., Key, N., Ribaudo, M., 2005. Managing manure to improve air and water quality. Economic Research Report 9. Economic Research Service. Available online at: http://www.ers.usda.gov.

Bahar, B., Monahan, F.J., Moloney, A.P., O'Kiely, P., Scrimgeour, C.M., Schmidt, O., 2005. Alteration of the carbon and nitrogen stable isotope composition of beef by substitution of grass silage with maize silage. Rapid Communications in Mass Spectrometry 19, 1937–1942., doi:10.1002/rcm.2007 (Published online in Wiley InterScience (www.interscience.wiley.com)).

Baird, D., Ulanowicz, R.E., 1989. The seasonal dynamics of the Chesapeake Bay ecosystem. Ecol. Monogr. 59, 329–364.

Baker, A., Allen, E., 2006. Feed Outlook. Electronic outlook report from the USDA Economic Research Service. Available online at: http://usda.mannlib.cornell.edu/usda/current/FDS/FDS-11-14-2006.pdf.

Benyus, J., 2002. Biomimicry: Innoviation Inspired by Nature. Harper Collins, New York, NY, USA.

Bleken, M.A., Bakken, L.R., 1997. The nitrogen cost of food production: Norwegian society. Ambio 26 (3), 134–142.

Campbell, C., 2005. Predictions of peak of world oil production. Accessed online at http://www.hubbertpeak.com/campbell/.

Daly, H., 1990. Toward some operational principles of sustainable development. Ecological Economics 2, 1–6.

EcoNetwrk, 2007. EcoNetwrk A Windows-compatible tool to analyze ecological flow networks. Software available online at: http://www.glerl.noaa.gov/EcoNetwrk/.

Eghball, B., Power, J.F., Gilley, J.E., Doran, J.W., 1997. Nutrient, carbon and mass loss during composting of beef cattle feedlot manure. Journal of Environmental Quality 26, 189–193.

Fath, B.D., Killian, M.C., 2007. The relevance of ecological pyramids in community assemblages. Ecol. Model. 208, 286–294.

Fath, B.D., Patten, B.C., Choi, J.S., 2001. Complementarity of ecological goal functions. Journal of Theoretical Biology 208, 493–506.

Ferguson, R.B., Nienaber, J.A., Eigenberg, R.A., Woodbury, B.L., 2005. Long-term effects of sustained beef feedlot manure application on soil nutrients, corn silage yield and nutrient uptake. Journal of Environmental Quality 34, 1672–1681.

Fiscus, D.A., 2007. Comparative Ecological Modeling for Long-term Solution of Excess Nitrogen Loading to Surface Waters and Related Chronic and Systemic Human–Environment Problems. PhD dissertation. University of Maryland. Available online at: http://www.lib.umd.edu/drum/handle/1903/6791.

Gregory, K.E., Cundiff, L.V., Kock, R.M., 1994. Breed effects, dietary energy density effects, and retained heterosis on different measures of gain efficiency in beef cattle. Journal of Animal Science 72, 1138–1154.

Hao, X., Mir, P.S., Shah, M.A., Travis, G.R., 2005. Influence of canola and sunflower diet amendments on cattle feedlot manure. Journal of Environmental Quality 34, 1439–1445.

Kangas, P.C., 2004. Ecological engineering: Principles and Practice. Lewis Publishers, Boca Raton, FL, USA.

Larney, F.J., Buckley, K.E., Hao, X., McCaughey, W.P., 2006. Fresh, stockpiled and composted beef cattle feedlot manure: nutrient levels and mass balance estimates in Alberta and Manitoba. Journal of Environmental Quality 35, 1844–1854.

Mollison, B., 1996. Permaculture: A Designer's Manual. Tagari Publications, Tyalgum, Australia.

NASS, 2006. Livestock slaughter summary. Released March 3, 2006, by the National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture.

Odum, H.T., Odum, E.C., 2001. A Prosperous Way Down: Principles and Policies. University Press of Colorado, Boulder, CO, USA.

Peterjohn, W.T., Correll, D.L., 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65 (5), 1466–1475.

Pollan, M., 2006. The Omnivore's Dilemma. The Penguin Press, New York, NY, USA.

Post, D.M., 2002. The long and short of food-chain length. TRENDS in Ecology & Evolution 17 (6), 269–277.

Smil, V., 2002. Nitrogen and food production: proteins for human diets. Ambio 31 (2), 126–131.

Steinhart, J.S., Steinhart, C.E., 1974. Energy use in the U.S. food system. Science 184, 307–361.

Sterner, R.W., Elser, J.J., 2002. Ecological Stoichiometry: The Biology of Elements from Molecules to the Biosphere. Princeton University Press, Princeton, NJ, USA.

Szyrmer, J., unpublished data. See p. 33 in Ulanowicz (1986) cited below.

Tess, M.W., Kolstand, B.W., 2000. Simulation of cow-calf production systems in a range environment. II. Model evaluation. Journal of Animal Science 78, 1170–1180.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

Ulanowicz, R.E., 2009. A Third Window: Natural Life beyond Newton and Darwin. Templeton Foundation Press, West Conshohocken, PA, USA.

Ulanowicz, R.E., 2004. Quantitative methods for ecological network analysis. Computational Biology and Chemistry 28, 321–339.

Ulanowicz, R.E., 2002a. The balance between adaptability and adaptation. BioSystems 64, 13–22.
Ulanowicz, R.E., 2002b. NETWRK 4.2b: A Package of Computer Algorithms to Analyze Ecological Flow Networks. Software documentation available online at: http://www.cbl.umces.edu/~ulan/ntwk/netwrk.txt.
Ulanowicz, R.E., 1999. Life after Newton: an ecological metaphysic. BioSystems 50, 127–142.
Ulanowicz, R.E., 1997. Ecology the Ascendent Perspective. Columbia University Press, New York, NY, USA.
Ulanowicz, R.E., 1995. Ecosystem trophic foundations: lindeman exonerata. In: Patten, B.C., Jorgensen, S.E. (Eds.), Complex Ecology: The Part–Whole Relation in Ecosystems. Prentice-Hall, Englewood Cliffs, NJ, USA, pp. 549–560.
Ulanowicz, R.E., 1986. Growth and Development: Ecosystems Phenomenology. Springer-Verlag, New York, NY, USA.
Ulanowicz, R.E., Baird, D., 1999. Nutrient controls on ecosystem dynamics: the Chesapeake mesohaline community. Journal of Marine Systems 19, 159–172.
Ulanowicz, R.E., Bondavalli, C., Egnotovich, M.S., 1997. Network Analysis of Trophic Dynamics in South Florida Ecosystems, FY 96: The Cypress Wetland Ecosystem. Annual Report to the United States Geological Service Biological Resources Division, University of Miami Coral Gables, FL 33124. Ref. No. [UMCES]CBL 97-075.
Ulanowicz, R.E., Kemp, W.M., 1979. Toward canonical trophic aggregations. Amer. Nat. 114, 871–883.
U.S. Census Bureau, 2006. Population Finder website, 2005 population. Accessed 11/29/06. http://factfinder.census.gov/servlet/SAFFPopulation?_sse=on.
USDA, 2006a. U.S. Department of Agriculture, Agricultural Research Service. National Nutrient Database for Standard Reference, Release 19. From Nutrient Data Laboratory website, http://www.ars.usda.gov/ba/bhnrc/ndl.
USDA, 2006b. U.S. Department of Agriculture. Agricultural Outlook: Statistical Indicators. Data available online at: http://www.ers.usda.gov/Publications/Agoutlook/AOTables/.
USDA, 1998, Nutrient Database for Standard Reference – Release 14. Continuing survey of food intakes by individuals, 1994–1996, 2 days. Nutrient Data Laboratory. Beltsville Human Nutrition Research Center, Agricultural Research Service, U.S. Department of Agriculture.
Vasconcelos, J.T., Greene, L.W., Cole, N.A., Brown, M.S., McCollum, F.T., Tedeschi, L.O., 2006. Effects of phase feeding of protein on performance, blood urea nitrogen concentration, manure nitrogen:phosphorus ratio and carcass characteristics of feedlot cattle. Journal of Animal Science 84, 3032–3038.
Wulff, F., Ulanowicz, R.E., 1989. A comparative anatomy of the Baltic Sea and Chesapeake Bay. In: Wulff, F., Field, J.G., Mann, K.H. (Eds.), Network Analysis in Marine Ecology. Springer-Verlag, Berlin, pp. 232–256.
Zorach, A.C., Ulanowicz, R.E., 2003. Quantifying the complexity of flow networks: how many roles are there? Complexity 8 (3), 68–76.