Abstract

Title of dissertation: Comparative Ecological Modeling for Long-term Solution of Excess Nitrogen Loading to Surface Waters and Related Chronic and Systemic Human-Environment Problems

Daniel A. Fiscus, Doctor of Philosophy, 2007

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Concurrent environmental problems including 1) excess CO_2 emissions and climate change, 2) excess nitrogen export and eutrophication of surface waters, and 3) dependence on non-renewable fossil fuel energy supplies can be considered interdependent symptoms of a single systemic “humans in the environment disorder”. This dissertation presents results from three integrated research projects to frame and solve this general human-environmental problem. As an interdisciplinary whole, the projects help define and characterize organizing principles for future human-environment systems without major carbon (C), nitrogen (N), energy and related problems. Forests and other non-human ecosystems provide model systems, as these communities self-sustain for 10,000 years and longer. Comparative studies of soils, C and N emissions, and food web networks provide transferable principles to guide local action for sustainability. Soils in long-term forest land-use stored more C and organic matter than soils in long-term agricultural use. These results recommend permaculture, agroforestry and perennial agriculture to provide food and other human needs while building soil and enhancing soil fertility. Audits of the Appalachian Laboratory in Frostburg, MD, showed this environmental science facility causes emissions of 70 times more C and 60 times more N than local forests can absorb. The Lab also is 99% dependent on non-renewable energy sources. This study provides data necessary to alter operations toward environmental sustainability. Comparisons of the U.S. beef supply network showed unusually high network ascendency (a whole-system efficiency measure), higher dependency on a few compartments and lower network connectance than four non-human food webs. Results support efforts to increase U.S. food supply reliability via local agriculture and diversified food network pathways. Overall, the research identifies a systemic cultural cause of the human-environment crisis in subordination of environmental value, quality and capacity to values in economic, social, scientific and other arenas. Elevation of environmental value to equal standing with other human values thus promises a solution to the global ecological crisis. Realization of such a cultural paradigm shift likely requires revisions to fundamental scientific definitions, theories and understanding of life, evolution and ecology, all of which now operate with a predominantly organismal model of life that likewise de-emphasizes the environment.

Comparative Ecological Modeling for Long-term Solution of Excess Nitrogen Loading to Surface Waters and Related Chronic and Systemic Human-Environment Problems

by

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Dedication

For my family: Tracy, Bailey, Sean, Cole, Jane Fiscus, Guy Fiscus and Josie Arias.

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Chapter 1

Comparative Ecological Modeling for Framing and Solving Excess Nitrogen Loading to Surface Waters and Related Chronic and Systemic Human-Environment Problems

Introduction

This chapter presents introductory material, literature review and conceptual overview for a three-part research project intended to help understand causes and create lasting solutions for current pervasive environmental problems such as excess nitrogen loading to surface waters. The three projects as a whole propose the need for, and outline a process for achieving, a major course correction in science and environmental science as key components of the collective intelligence of society. Results from this work are expected to assist efforts to change science's enabling and participatory causal role in the current human-environmental crisis so that science can more effectively help create and demonstrate lasting solutions to these problems.

The three projects employ comparative ecosystem studies or comparative ecosystem modeling. Comparing problematic human ecosystems to successful natural ecosystems like forests may help us decide if we can continue our current general human-environment relationship, if we need to make fundamental changes, what specific changes could improve environmental quality, and what successful ecosystems exist that can serve as role models.

The bulk of evidence from many workers and disciplines globally seems to suggest the future will be like the past – our physical basis will be like subsistence communities prior to fossil fuels, or like forests and other natural communities now, that run on renewable energy and recycling materials processes. While it is unknown whether technological advances may alter this scenario, it seems most prudent and responsible to actively develop and pursue a strategy to convert to a more modest, less resource intensive standard of living. One can still hope for and seek to develop technological breakthroughs able to allow further extensions and development of the human enterprise, but to treat such advances as inevitable and depend on them coming true would be more like a faith-based and reckless belief than an evidence-based and precautionary plan.

Characterizing and Addressing the Environmental Crisis

The Millenium Assessment (Millenium Assessment 2005) stated that 60% of the ecosystem services (e.g., air, food and water processes, capture fisheries) needed by humans are now “being degraded or used unsustainably”. The World Scientists Warning to Humanity (UCS 1992) warned that humans and the natural environment are on a “collision course” and that fundamental change is required to avoid catastrophic disaster. Excess nitrogen, phosphorus and sediment loading from land to the Patuxent estuary, Chesapeake Bay and similar water bodies has resulted in multiple forms of environmental damage, such as algal blooms including toxic species, anoxia, fish kills, reduced fisheries harvests, reduced water clarity and harm to aquatic vegetation, among other problems (Jordan, et al. 2003, Driscoll et al. 2003).

The view of many scientists who have assessed the general human-environment situation is that our current configuration or ecological strategy is not working and is inherently unsustainable. The final seminar in the 2005 Chesapeake Bay Seminar Series organized by the Integration and Application Network (ian.umces.edu) was given by Peter Leigh and was titled “The ecological crisis, the human condition, and community-based restoration as an instrument for its cure.” In the published paper that goes with this seminar, Leigh (2005) writes:

> There is a growing belief that the global ecological crisis which confronts humanity today is one of the most critical turning points that human civilization has ever faced. The causes of this trend are believed by some to lie in environmentally destructive propensities that create ecological imbalances. The basis for these imbalances can be ascribed to many forces, but can be largely reduced to a few central trends, the intensity of human consumption multiplied by sheer human numbers, combined by the lack of will to change, or worse, to fundamentally understand how our behaviors today are producing tomorrow’s problems. None of these forces appear to be receding as global population and human consumption continue unabated with societies more inclined to watch, register, and witness these trends than to actively seek solutions.

Leigh’s mention of a lacking capacity to “fundamentally understand” is perhaps the part most relevant for environmental science and science in general, the fields in which we are actively working to increase understanding of behaviors and their problematic consequences, the relations between causes and effects and the correlations between various independent and dependent variables.

Leigh (2005) is not the only one to frame the human-environment problem in such broad and general ways. The point we now find ourselves in the history of the world has been described as The Great Turning (Macy 2005), The Great Transition (Raskin et al. 2002) and the Second Industrial Revolution (McDonough and Braungart 2002). All of these metaphors relate to a predicted qualitative transformation of modern industrial culture from unsustainable environmental and inequitable socioeconomic relations to sustainable environmental and equitable socioeconomic relations. Our current period also has been described as a threshold crossing from an “empty world” to a “full world”

(Goodland and Daly 1996), in which for the first time ever, the scale of the human enterprise and its collective impacts on the environment have matched the scale of the planet. In the new "full world" these authors depict, resources and waste assimilation capacity of the world can no longer be assumed to be infinite in supply.

So the problem is big, fundamental and likely to get worse. Several leading thinkers see major transition processes now or soon to be underway for developed human societies. In the words of Odum and Odum (2001):

> Soon the United States and other developed nations will begin their descent, learning how to live with less emergy [a measure of energy] and a smaller economy. 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.
>
> Our energy review…left little doubt that downturn will occur. Instead of denial, it is time for people at all levels of society to plan for a better world in which we use less. There should be task forces throughout society working on descent.

This vision and proposed direction – toward a "better world in which we use less" - is a working hypothesis for the correct strategy, but the author is also open to being shown otherwise. The suggestion above that we may "get some ideas observing ecosystems" supports the comparative ecosystem studies and applications of Mollison (1996), Jackson (1994) (discussed more below) and others. This approach asserts that the general organization of natural systems seems to hold promise for organic, self-sustaining solutions, if we could learn how to translate them to human systems.

Based on the logic and payoff matrix for risk analysis given inherent uncertainty Costanza (2000) also showed that the most prudent strategy is to plan for and act to adapt to the low energy case. This is true because the downside risk of the main alternative is so very negative. That is, to plan for or assume a techno-optimist future of continued high energy but then have the reality turn out to be the low energy case would lead to catastrophic problems due to overshoot and collapse of life support capacity. On the other hand, if we plan for the low energy case and some new inventions enable more energy, there is no comparable negative impact from that choice and set of actions. Thus the position adopted here is that the responsible way forward is to plan for the low energy context and hope for the best (cold fusion or other techno-miracle).

While nitrogen export, mentioned above as critical for the Chesapeake Bay, provides an important and information-rich specific problem and key symptomatic behavior, it is important to note that problems with energy, C, water and still more other factors (e.g., soil loss, toxic chemicals, habitat loss, biodiversity loss, invasive species, etc.) suggest a more systemic problem in general and widespread unsustainable human-environment relations. Ackoff (1974) provides guidance here on the approach to identifying and solving such complex problems:

> English does not contain a suitable word for "system of problems." Therefore I have had to coin one. I choose to call such a system a "mess.” The solution to a mess can seldom be obtained by independently solving each of the problems of which it is composed.

In this spirit, the proposed research seeks understanding to help solve the whole system of human-environmental problems, to clean up our environmental mess taken as a systemic whole.

Environmental Sustainability as Integrative Concept and Litmus Test

At this point definition of environmental sustainability as employed and assumed here may help. One quick and basic, but still robust and relevant, definition of environmental sustainability requires that a given process, community or system 1) use renewable, net energy and 2) use recycling materials processes. Goodland and Daly (1996) provide another parsimonious set of criteria for truly sustainable human-environmental systems in their Input-Output rules:

> **Output rule.** Waste emissions from a project must be within the assimilative capacity of the local environment to absorb without unacceptable degradation of its future waste-absorptive capacity or other important services.
>
> **Input rule.** A. Renewables: harvest rates of renewable-resource inputs should be within the regenerative capacity of the natural system that generates them.
> B. Non-renewables: depletion rates of non-renewable-resource inputs should be equal to the rate at which renewable substitutes are developed by human invention and investment. Part of the proceeds of liquidating non-renewables should be allocated to research in pursuit of sustainable substitutes.

While these definitions are useful and meaningful, one goal of this work was to develop a stronger formulation – *the necessary and sufficient conditions for local environmental sustainability*. Such a rigorous concept should aid debates in environmental science as we seek to “convince ourselves” of what sustainability is, whether it applies to us and whether it should become a strategic priority. After such an internal consensus and commitment to self-change action, a restatement of sustainability that has few or no loopholes would also aid in convincing others of the importance of the general destination of environmental sustainability as well as the specific criteria needed to chart and maintain a course in that direction.

Sustainability Reverses Conventional Wisdom

The logical, ostensibly factual and seemingly physically inevitable imperative of sustainability can be seen with relatively simple thought experiments and observations. By simple virtue of requiring 1) quantitative accounting for *long-term trends* in production and 2) accounting for gains and losses of *productive capacity* for such ecosystem services as agricultural products, timber, water and air supplies, as well as all production based on non-renewable energy, the idea of sustainability challenges most of our current assumptions about how human society operates and how well we are doing. Without consideration of these sustainability factors, conventional agriculture, for example, appears as a successful solution to the problem of feeding a large population efficiently. The so-called “Green Revolution” of intensive, industrial agriculture is often touted as a shining human achievement (Shore, 2005). But once the long-term and productive capacity factors are considered, an assessment of conventional agriculture changes qualitatively and dramatically – it becomes more a problem than a solution, a net negative, detriment or loss for society as a whole. The same reversal appears to occur for any societal system that performs a function that is needed long-term and depends on finite, non-renewable fossil fuels for its operation.

If we dig below the surface of conventional agriculture, we see that each annual enactment of the management-production-harvest cycle depletes crucial components of the *capacity for production* in the forms of 1) soil organic matter and soil carbon and 2) fossil fuel energy, among others we could list. It then becomes evident that the short-term production and profit gains have come at the expense of a long-term loss in production capacity. In economic jargon, such a system as an enterprise consumes its own "capital" rather than preserving and "leveraging" capital to generate production and income. Such a production process cannot continue indefinitely – is not sustainable over time - because with iteration the basis for production, the capital or capacity, is depleted. The issue of substitutability may be raised to dismiss this problem, but it seems more reasonable to assume 1) there are no substitutes or equivalent replacements for soil organic matter or fossil fuel energy, 2) these physical assets are required for production, they are not optional or expendable, and 3) even if substitutes for these specific assets could be found, the relational fact of a decreasing trend of assets with production would remain the main problem. Given these assumptions, *conventional agriculture is a problem to itself* – it limits its own future existence and prospects by degrading its own capacity as it operates. This seems equally true for any production system (e.g., industry, medicine, science, housing, etc.) that consumes its own biophysical capacity for production, such as any system that depends on finite, non-renewable energy and does not replace comparable energy capacity in its process.

The picture gets worse. A production system that depletes its own capacity has a self-limited, declining future trajectory for itself. In addition (again for the representative example of agriculture) a problem is caused by the fact that *production enables population growth* – the food is not merely an end in itself, but also enables the "making of people" (Quinn and Thornhill 1998). So as time progresses, two diverging trends occur: 1) the capacity to produce (food) *declines*, and 2) the number of people needing the production or services (food) *increases*. Thus *conventional agriculture is a problem for society* – it creates an increasing gap between the supply and demand of food.

The picture gets worse still. In addition to the above problems, agriculture, fossil fuel based and other such extractive, consumptive, short-term production systems *emit harmful pollutants as they operate*. Some of the capital or productive capacity that is burned, consumed or depleted leads to byproducts that are released into atmosphere, soil and/or waters and many times lead to other negative consequences. Examples are 1) increasing atmospheric CO_2 and problems associated with climate change and global warming and 2) excess nitrogen runoff from agricultural and developed lands causing eutrophication of receiving waters such as the Chesapeake Bay. Thus *conventional agriculture is a compound problem, a double whammy for society* – it causes 1) a future gap between the supply and demand of food while also 2) creating pollution problems that limit and impede food production and other aspects of life, life support and the quality of life. Thus any system that provides a so-called benefit to people via a process that cannot be continued long-term creates an *internal societal dependency* in the form of an eventual “demand greater than supply problem”. And any system that pollutes during production also makes matters worse by creating an *external environmental vulnerability* as life support and ecosystem services are degraded.

Formalizing and Modeling Sustainability

Another of the working assumptions about what is effective and how best to conceive of sustainability is to define sustainability in reference to a relatively small local area. A general idea of the spatial scale in mind is a small human community, a small watershed, or a small forest. The towns of Cumberland and Frostburg, and Fifteen Mile

Creek watershed, all in Western Maryland, would fit within this rough spatial size range. As discussed more below, this local approach is essentially the most conservative and rigorous. While there are regional and global factors that are important to what is sustainable in any locale (e.g., processes that determine weather, precipitation, atmospheric deposition and many other factors), the local actions and local organization of a community are the factors that are most amenable to design, modeling, community organizing and action for change.

While sustainability may include matters that are subjective, value-asserting and ethical – *matters of conscience* – it also seems valid to say that sustainability involves other factors that are objective, value-comparing and rational – typical *matters of science*. For example, Bill Mollison (1996) speaks of the motivation for adoption of his proposed form of sustainable human-environment relation, permaculture, as strongly ethical. He wrote:

> The Prime Directive of Permaculture
>
> The only ethical decision is to take responsibility for our own existence and that of our children. **Make it now.**

This concise principle fits with other widely used definitions of sustainability such as that in the Brundtland Commission (1987) report which defined sustainable development as "Development that meets the needs of current generations without compromising the ability of future generations to meet their own needs." As strong, compelling and seemingly self-evident as Mollison's directive is in its appeal to one's conscience, it still leaves questions pertinent for and requiring exercise of one's science or the collective intelligence of a human community. *Exactly how do we go about taking responsibility for* *our children and ourselves? With what first principles or basic knowledge of the world would we build an action program to make good on this directive? Of the many things that our children and we need, in both the short- and long-terms, how would we best prioritize in providing for these needs?*

Interestingly, Mollison (1996) also bases permaculture on a creative mental approach of treating forests as “system analogies” on which to model human agriculture and culture in general. Mollison, an ecologist who grew up in a small self-reliant fishing town in Tasmania, describes the origin of his concept of permaculture in his autobiography:

> In November 1959, watching marsupial browsers in the floristically simple rainforests of Tasmania, I wrote in my diary: "I believe that we could build systems that would function as well as this one does."
>
> A casual reflection, not further developed, had broken the barrier between passive observation (in an attempt to understand inter-relationships between browsers and plants) and the active creation of many similar systems that we could construct ourselves.
>
> The step from passive analysis to active management or active creation was critical. I was also discovering over this period (1959-1962) that even two of these common browsers and no more than 26 woody plant species could set up a series of very complex interactions. Thus, it was the interactions of components rather than the number of species that gave the system its flexibility. That flexibility allowed a fairly stable condition to be established through a variation in other influences, in weather and growth. The system constantly changed but continued to function.
>
> This then was both the precursor and the core of Permaculture; the realisation that we can create systems based on analogies of natural systems, or try to improve them for productivity, and then allow the created system to demonstrate evolutions, stepping in at critical stages to manage, add or subtract species, and observing at all times.
>
> These system analogies, if well constructed and recorded, could produce a yield that could be constantly assessed or improved, and would also need minimal maintenance energy, after the established phase.

Thus permaculture proposes rational and scientific design and operation guidance by which human agricultural and other systems could be organized using a forest as a systems analogue or systems archetype (Wolstenholme 2003, Sweeney and Meadows 1995, Senge, 1990). And in the totality of his works, Mollison further makes the connection that this type of scientific, intelligent systems design is the best way, provides the necessary and sufficient tools needed, to take responsibility for the ecosystem services crucial to the continued life of our children and ourselves. In this sense sustainability is at the nexus of what is good (responsible, via conscience) and smart (intelligent design and management, via science) for how to live on Earth and leave land as good or better than one found it.

A fundamental value asserted in this research is that environmental resources, ecosystem services and life support needs are of equal or higher value and priority than other needs such as those in social and economic realms. Following Goodland and Daly (1996), the value of environmental life support and its ongoing availability are taken to be “universal and non-negotiable”.

Oddly it seems that environmental sustainability is more often treated as optional, negotiable, of concern only to special interest groups, or in conflict with “higher” priorities such as economic growth or the short-term preservation and ease of human life. Sometimes sustainability is even treated as impossible. One successful, highly educated strategic economic consultant to the city of Cumberland commented, “…all systems must consume…”, implying that a negative balance and increasing deficit in natural resources is the only possibility for modern cultures. This same economist also stated that environmentally sustainable, self-reliant living is observed only in a tiny majority of aboriginal and subsistence cultures (Steve Mullins, personal communication). The view taken here is essentially the opposite, and the works cited here suggest a reversal of such conventional economic wisdom is necessary. Instead of looking at what we do now and saying sustainability is impossible, we may need to begin considering what is sustainable and change our activities so that we are doing that. And without an explicit and conscious intention to achieve sustainability, it seems guaranteed that we will not live, act or make choices in such way to achieve sustainable human-environment relations. Conversely, only if we actively and consciously intend to be sustainable is it likely to come true. In this sense our intention is very much a self-fulfilling prophecy.

At the most basic level, the two-way relationship between a living community and a local environment may vary similar to the nine interaction types possible between two organisms that affect each other positively, negatively or neutrally (Ulanowicz 1997). The local environment always aids a living community in some way (e.g., via solar energy, gas exchange, local nutrients or merely living space) and so this half of the relationship is always positive. The living community may be considered to affect the local environment positively, negatively or neutrally. Such value, sign or quality determinations can be made based on reference to what is positive or negative for the living community. Thus a positive impact on the environment is one that in turn aids the living community in areas such as production or resilience. This may seem circular, and it is, but this approach is suggested to be circular in a good way rather than either a trivial or pathological way. To define what is good for the environment relative to what is good for the living community that depends on that environment is to both internalize the environment and to invoke impredicative or “chicken and egg” processes (Giampietro 2004, and see below). Given this perspective, there are three possible community-environment relationships: 1) mutualistic, both impacts are positive and beneficial, symbolized by a +/+ relationship, 2) commensalism, in which the environment aids the community and the community has no effect on the environment, symbolized by a +/0 relationship or 3) predatory, parasitic or antagonistic, in which the community has a negative impact on the environment, symbolized by a +/- relationship (Odum 1983).

One working assumption developed and tested here is that the mutualistic relationship is the best generic concept for sustainability. This relationship seems most similar to the forest-environment relationship in that forests accumulate local soil stores of C, N and organic matter, which are known to aid ecosystem production. The commensal model is ignored for now but could also be considered basically sustainable (although more susceptible to disturbance in that with no improvement of the environment, no reserves or buffering capacity is built up). The antagonistic relationship is clearly different from the mutualistic relationship and seems most similar to the general human-environmental relationship at this time in which basic environmental capacities necessary for human communities are being depleted (e.g., fossil fuels, soils, biodiversity) or degraded.

Environmental Science as Both Speaker and Audience

A key portion of this work is self-reflexive for environmental science. It suggests that environmental science could benefit from intensive dialogue on how best to lead society through complex contemporary decisions and into a more sustainable future. The research provides fundamental information about quantitative, physical aspects (i.e., biophysical carrying capacity) as well as qualitative, relational aspects (i.e., organizational form and dynamic behavior) of locally environmentally sustainable human-environment systems – including the buildings and campuses of academic science operations. A key working assumption is that if we in environmental science can solve excess nitrogen emission and the intertwined energy, carbon and water problems in-house, the spreading of success stories and functional solutions to other sectors of society ought to be much easier in comparison.

One of the ultimate goals of the research proposed here is to ask whether environmental science, and society as a whole, would be well served by a thorough and honest self-examination of environmental science by environmental science. This question is raised with hopes of both improving the quality of science in environmental science as well as improving the ability of environmental science to deliver on its potential to help solve the major environmental crises now facing humanity. The proposed approach for environmental science is seen as a smaller subset within a larger self-examination for all humanity.

Hubbert (1976) depicted the environmental and historical context in which we find ourselves at the turn of the 21st century. His graphs of energy use and human population place us at the pinnacle of civilization based on the crucial metric of energy. We cannot know for sure what the future brings in specifics, whether energy and human population will trend more like his projections in curve I (continued growth and plateau at a higher level), curve II (moderate reduction and plateau at an intermediate level) or curve III (precipitous decrease and collapse), but it seems highly likely that our general direction will be down, with major ramifications for all aspects of culture, society and daily life. Environmental science and ecology possess accumulated knowledge that potentially can help us to know which direction, in what forms, and at what speed future human-environmental development ought to proceed. But we are caught in this same context, the large-scale and unique historical dynamics, with the rest of life on Earth.

The gist of the collection of ideas here is to ask if the causes and solutions to our environmental problems are equally or more likely to be “in here”, in our own minds and values, as well as “out there”, somewhere else, objective, in the world. In essence this work asks of environmental science, *Can we really help others before we have our own environmental “house in order”? What would it take to get our own environmental house in order, to achieve environmental sustainability of our own operations? Would it perhaps be easier and more effective to develop and spread solutions to other sectors of society after we have first developed and tested functioning solutions and achieved success in our own environmental science institutions?*

While it may seem the environmental problem being framed here is skewed, overly self-conscious or of interest only to a minority in terms of being highly philosophical, subjective or narrow, it may also be that the issues raised and approach taken are in fact highly scientific, objective and general. For example, the problem as framed above is akin to asking, *How do we sustain environmental science (as a subset) and human society (as a whole) in terms of fundamental energetic and biogeochemical relations?* And this question could potentially be generalized further. Related questions include: *How does any process, community or system sustain itself over the very long term? How can any process or system maintain or increase its productive capacity as it achieves production? How can any system increase its assets, potential, relative* *environmental standing or odds of survival in the future? How can any system improve itself, its environment and its relationship to the environment as it operates?* These questions in turn are not far removed from some of the most fundamental questions of all such as, *What is life?* (Shrodinger 1944).

As applied to society as a whole and environmental science as a subset such questions raise a metaphorical question of what we should expect for trends over time. *Must we accept decay and degradation of our communities, ecosystems and environment as we operate* – much like we normally expect for a machine that wears out, breaks down and uses up quality energy – *or should we aim higher and expect improvement and enhancement of our communities, ecosystems and environment as we operate* – much like we normally expect for living muscles that get stronger with use, forests that build soils and biodiversity as they produce or other life systems that similarly sustain and enhance self, environment and self-environment relation simultaneously?

A version of this question that links both the most immediately applicable and the most lastingly theoretical questions may be, *What is the best ecological strategy or organizational form for systems that wish to "live long and prosper"?* Via such connections the questions addressed here have been developed because the author over many years of research has seen questions of this type to be both "theoretically deep" and "widely applicable" - one can follow them "downward" to very fundamental issues of basic theory and scientific understanding of the original and fundamental nature of life and life-environment relations, and one can look "outward" almost anywhere on Earth and see that the questions, problems and solutions sought are relevant for practical human needs.

The Ecological Organizational Form of Environmental Science

In the current state of the art for the physical form of environmental science itself, as we work to increase understanding, educate the next generation and solve problems, two main schools of thought exist. Based on personal experience, most environmental science institutions do not scrutinize their own environmental needs and impacts. Mainly, environmental science seems to ignore its own place and interactions in environmental contexts. In contrast, a very few universities and research centers have decided that the environmental demands and legacies of their own operations are crucial issues. These institutions have begun to examine, monitor and also convert their own operations to more sustainable, less consuming forms. Oberlin College, the Woods Hole Research Center, and the Sustainability Institute are examples. The latter (founded by Donella Meadows, a systems modeler who co-wrote the important book, Limits to Growth (Meadows et al. 1972)), was designed to be a "think-do tank" rather than simply a think tank. In addition to science and policy research related to environment and sustainability, the Sustainability Institute also has "green design" housing and an organic farm on the same property. Thus environmental science research is here integrated with other components in a larger human-environment community that is much more locally sustainable than most.

Success in science is simple and straightforward to describe, if very difficult to achieve. One group of authors has described development of new major paradigms in science as requiring "careful and ingenious experiments, replication across laboratories, good arguments and the conversion of the next generation" of scientists **(**Gopnik et al. 1999**).** This description of one of the major evolutionary or developmental processes in science does not include any mention of the *capacity to do science*, environmental costs or values. Much like mainstream economics, most practitioners and approaches to science have "externalized" environmental costs. That is, expenditures of environmental capital and "depreciation" of natural resources are removed from consideration when assessing progress and success. Even within environmental science there has been very little explicit and conscious accounting of environmental costs or tracking of trends in the environmental resources required for conducting science, such as supplies of energy, carbon, nitrogen and water. Instead, other measures are used for evaluation of success and progress, such as numbers of papers published, students advised and grant dollars brought in.

For example, the process to complete and receive a PhD in environmental science does not require any accounting or evaluation based on the energy or material expenditures made during coursework, research or writing. A student's PhD program that consumed 5000 kilowatt hours of coal-generated electrical power and emitted 1000 kg of reactive nitrogen into the atmosphere and water would not be differentiated or qualified by any existing process from a PhD which consumed 500 kilowatt hours of wind-generated power and emitted 10 kg of N. These environmental costs currently are not internal, are not deemed significant, or are not valued as integral to the process of attaining the highest level of knowledge in environmental science.

It seems science may get trickier and more complex if we begin to internalize rather than externalize environmental costs. Considering such a revised approach, one must also decide on spatial and temporal extents or boundaries with which to define an entity as well as the environment from which, and time frame over which, it receives its needed supplies and emits its wastes. In perhaps the most conservative approach, determination of both environmental supplies and wastes are local and also place-based, and any such accounting must be integrated with specific details of the local environment. That is, if one excludes the option for subsidies from afar and requires that a science enterprise operate based on ambient energy (current solar income) and material sources arriving at a fixed locale, then one in essence requires that environmental sustainability be local environmental sustainability. This conservative requirement is compatible with the input-output rules for sustainability of Goodland and Daly (1996). If this criterion is applied to science, it implies that the operational, physical form of science would have to be largely dependent on details of the local context of science, which varies from place to place. Much like variations between the form of forests in tropical, temperate and boreal regions, science integrated with and sustainable in local environments would seemingly need to change form in concert with the real environmental context in which the science is conducted.

As mentioned above, two schools of thought differ in their approaches to examining versus ignoring environmental costs and the sustainability of environmental science itself. This disagreement or schism within environmental science suggests 1) that more institutions may begin to consider this issue and may be seeking to choose between these two paths, and 2) that additional information on these two alternatives could aid in decision making and choosing a direction and course of action.

Action Orientation - What Needs To Be Done?

It may be useful to consider the major actions needed by environmental science with respect to the ecological crisis, and then ask what knowledge is needed or missing that would help us choose our course of action.

Environmental science in its most general form involves research, discovery, education, public service, and development of applications to problem solving, management and policy. Environmental science faces a formidable challenge now in the efforts to help solve widespread, chronic, systemic environmental problems of unsustainable human-environment relations in general. The current approach often seeks to solve isolated, more specific human-environment problems such as excess N loading from land to water (Jordan et al. 2003, Galloway et al. 2003, Cowling et al. 2001, Driscoll et al. 2003), excess CO_2 emissions (Friedlingstein and Solomon 2005), dependency on finite fossil fuel energy sources (Campbell 2005), and unsustainable use of fresh water (Gleick 1998).

All of these environmental science research efforts are clearly important and valuable to society. Restoration of environmental quality for the Chesapeake Bay was first estimated to cost $19 billion (Blankenship 2002), but this estimate was later increased to $29.3 billion (Blankenship 2004). Some good progress is being made. Figure 1.1 shows dramatic decreases in N export for the Patuxent River at Bowie from 1985 to 1995 down to concentration levels of about 2 mg per liter. However, this figure also suggests that a plateau in decreases, and perhaps a linked limit to improvements possible from current management approaches, has been reached. For comparative ecosystem reference, baseline N export from forested watersheds is also shown (although it is barely visible as it blends into the X-axis). These much lower N concentration rates (which result in much lower export or flux rates) average 0.05 mg per liter in Virginia (Eshleman et al. 2001) and 0.01 to 0.03 mg per liter in North Carolina (Swank et al. 1981). These rates are 40-200 times lower than for the highly developed and agricultural Patuxent watershed.

Existing understanding and treatment of excess N loading lead to management recommendations that focus largely on 1) efficiency of N use and 2) reduction of N emissions and resulting atmospheric deposition. Driscoll et al. (2003) propose a suite of options including biological nutrient removal of N from wastewater, increasing efficiency of N use in agriculture and emissions reductions in transportation and electrical power utilities. A few studies suggest more fundamental reforms such as revising flow routes to recycle more reactive N back onto agricultural lands and addressing linkages with other nutrient cycles such as carbon, sulfur and phosphorus (Cowling et al. 2001). Some of the most radical proposals for solutions come from workers who suggest a total reorganization of human systems to mimic the structure and function of natural systems.

In essence what needs to be done is that we must make quantum leaps in improvement in the most basic aspects of health of the human-environment relation. For

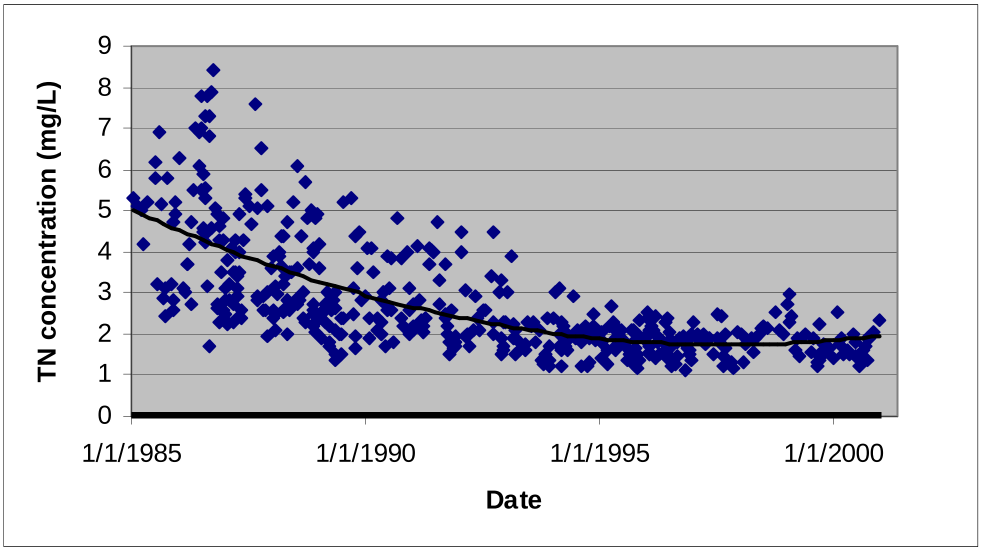


Figure 1.1. Total nitrogen (TN) concentration in the Patuxent River at Bowie, 1985-2000. Data from Chesapeake Bay Program (Fisher et al. 2005). Comparison reference level for TN levels typical from forested watersheds is shown as thick line near X-axis at 0.05 mg per liter, 40 times less than the apparent plateau at 2 mg per liter for the heavily human-dominated Patuxent watershed.

example, we must find new forms of applied environmental science to enable us to get beyond our current limitations as indicated in the resistance of N export for the Patuxent to get below the current plateau level. And while excess N is one major symptom, excess CO_2 emissions, energy and water problems are all inseparably related. Production of N fertilizer requires large amounts of energy and in turn results in CO_2 emissions. Excess N is carried from land to surface water by rainfall and runoff and via groundwater. The list of interdependencies could go on. Without reliable, resilient and regenerative environmental processes to supply energy, air, water, food and other necessary resources, human society would cease to be viable. Meadows et al. (2004) suggest that humanity is currently 20% beyond environmental carrying capacity. In other words, it would require 1.2 Earths to provide the necessary resources to support the current global population. Environmental science is clearly among the core disciplinary fields of expertise from which solutions to such fundamental human-environment problems must come.

What Is Known?

We can consider the state of existing knowledge in terms of 1) basic environmental processes, problems and solutions and 2) the best way to conduct daily environmental science operations. The former will be discussed first.

Nitrogen export from watershed ecosystems is a useful integrative indicator of ecosystem status and function (Likens et al. 1970, Eshleman 2000, Eshleman et al. 2001) because of 1) the myriad negative effects downstream from excess N loading 2) the multiple factors of internal organization that must be present to enable efficient and resilient N retention, and 3) the seeming ability of N export to differentiate between healthy and undisturbed versus problematic and disturbed terrestrial ecosystems. Research has shown the consistent relationship between levels of N export and proportions of forested, agricultural and developed land use types (Driscoll et al. 2003). In general, the greater the percentage of forest cover the lower the N export (Langland et al. 1995).

One fruitful approach is comparative ecosystem studies – to study similarities and differences in structure, function, behavior over time and organizing principles of different ecosystems and human or natural communities. Using this approach, one may ask, for example, how forested watershed ecosystems compare to human-dominated watersheds in terms of long-term environmental sustainability or health. Sustainability and health can be considered with a focus on N export and water quality, as in such factors as highlighted in the list below.

Forests achieve:

1. Effective maintenance and enhancement of water quality for multiple criteria simultaneously – e.g., low N, P and sediment export (as compared to multiple problematic behaviors simultaneously, such as excess N, P and sediment export from human-dominated watersheds).

2. Efficiency in water quality – use of renewable energy and recycling materials processes (as compared to use of finite fossil fuel energy and non-recycling materials streams in human systems).

3. Internal regulation or self-control of water quality (as compared to external regulation via government agency).

4. Resilient nutrient and sediment retention – self-control of water quality that is restored after major disturbances such as insect defoliation, logging or storms (as compared to resistant nutrient and sediment losses by human systems for which large management efforts have not yet resulted in large improvements).

5. Distributed, redundant and robust self-control of water quality (as compared to centralized government control with a single or a few points of failure and tendency for bottlenecks or backlogs of regulatory action).

6. Simultaneous achievement of other environmental functions in addition to water quality, such as production of wood/biomass, maintenance of biodiversity, self-enhancement of water quantity and processing, and retention and accumulation of soils (as compared to simultaneous occurrence of other problems in human systems such as losses of soils and biodiversity and problems with water quantity due to use rates greater than recharge rates, flooding, etc.).

Forest watersheds display impressive whole-system characteristics that seem an ideal model set or systems analogue (Mollison 1996) for self-enhancement of environmental health and water quality for which we might strive. And on almost all major points above, forests seem to succeed with elegance and excellence while human-dominated watershed ecosystems seem to fail miserably and to require large-scale remediation. While we cannot literally convert all land use to forest, this research in part seeks to ask if, and understand how, we can alter and reorganize human systems so that they behave and perform more like forests or other natural ecosystems on these key facets of environmental quality.

Beyond this comparison, a wider and more general consensus may be seen in the synthetic works of many environmental and ecological scientists, as well as workers from other fields such as economics, engineering and management. The following sets of publications or concepts all can be seen to apply to long-term environmental sustainability and healthy environmental function, although from many different angles.

Workers, Publications	**Key Concept, Result or Hypothesis**
1. Likens et al. 1970	Forested watershed homeostasis and maintenance of nutrient capital are due to 1) autotrophic and heterotrophic functional balance and 2) intrasystem cycling.
2. Aber 1999	Nitrogen flux in forested watershed ecosystems comes from local recycling to a much greater extent than input or cross-boundary flux
3. Goodland and Daly 1996	Propose input-output rules for environmental sustainability that treat local supplies, demands and capacities for energy, materials and waste assimilation. See their rules above.
4. Allenby and Richards 1994	Characterize Types I, II and III industrial ecosystems and relate Type III - with the highest degree of material recycling - to natural ecosystems and as the ideal model for industrial ecosystems.

5. Odum and Odum 2001	“Wherever we place the window of attention we can find systems of production, consumption and material recycle.” Production and consumption are integrally coupled in general and at all scales in ecological systems.
6. Odum 1971	The ecological system (production with consumption) precedes the origin of life, and is thus more fundamental or general than, and is able to generate, more specific subset life forms such as organisms and cells.
7. Fath et al. 2001	Ecosystems tend to maximize dissipation while also maximizing storage, which can be achieved simultaneously if residence time is also maximized.
8. Fath and Patten 1998	All networks with openness, symmetry and indirectness result in synergism such that most ecological relations are mutually beneficial rather than competitive or antagonistic when all direct and indirect interactions are integrated.
9. O’Neill 1987, Morowitz 1992	Define the ecosystem as unit of sustained, long-term or continuous life, as contrasted with cells or organisms as units of discrete or short-term life.
10. Ulanowicz 1997	Network ascendency tracks total system growth, size or throughput during the aggradation phase, but switches to track average mutual constraint or information during maturity and into steady state phase of ecosystem or community succession.
11. Ulanowicz 1997	All natural ecosystems are organized with network structures that fall within a “window of vitality”. These structures seem suited to operate in a middle realm between too much and too little order or constraint, a dialectic-like trade-off also shown in the complementarity of system ascendency and overhead.

12. Covey 1989	Maintenance of balance between 1) production and 2) productive capacity is a “natural law” that applies to most realms of life.
13. Mollison 1996, Jackson 1994	The best, most sustainable form of agriculture is one that is based on natural systems for a given locale as a systems analogue – e.g., a prairie in the Midwest U.S. or forests in places where forests naturally exist.
14. Fiscus 2001-2002	Current conventional agricultural systems fail to 1) use renewable energy, 2) recycle materials and 3) organize with coupled complementary processes such as composition-decomposition (autotrophy-heterotropy) and are unsustainable. Natural systems meet these three criteria and are sustainable long-term, as they have no inherent, internal self-limitation in terms of the “capacity for sustained production”.
15. Ksenzhek 1998.	“Photosynthesis and respiration, two complementary processes that provide for the functioning of a biosphere.”

One way to distill a consensus from these works is to say that long-term sustainability is a property that can make sense for a community, ecosystem or biosphere, but not for organisms or individual entities. (This distinction combined with the reality that humans are organisms may be responsible for a misperception that drives our ongoing confusion and environmental dysfunction. We may project our main model, metaphor or analogue of “life as organism” onto all operative units for environmental action (e.g., land development projects that add people and remove plants), so all actions or projects, like the organisms they are patterned after, die, decay and degrade. Such psychological issues are explored well by Leigh (2005), who relates current human environmental dysfunction to disorders like autism, delusion and schizophrenia.)

Another way to formulate a cross-cutting distinction is to say that sustainable systems may be those that successfully resolve conflicts between 1) short-term or short-lived forms, individual organisms or discrete parts of larger systems and 2) long-term or long-lived forms, communities of organisms in ecosystems or continuous wholes of larger systems. This distinction fits one made in prior work (Fiscus 2007a in preparation) that unsustainable systems fall prey to the “Tragedy of the Commons” (Hardin 1968) by pitting individuals against communities in a zero sum game, whereas self-sustaining natural systems seem to act out and achieve a “Bounty of the Commons” in which both individuals and communities survive and thrive in synergy in a win-win game.

The current state of knowledge of environmental processes, problems and routes to solution include, among other currencies or metrics, energy, N, C and water. These four major environmental resources provide a strong set of measures that are crucial for long-term sustainability of coupled human-environment systems. As suggested by its inclusion in many of the works above and by its integrative nature, excess N loading is a good candidate for a parsimonious set of environmental indicators by which to gage, monitor and restore whole-system health and sustainability.

For the case of excess N loading from land to water, several major factors have been studied extensively. The effects of 1) forest disturbance and internal system alteration (e.g., clear cutting (Likens et al. 1970), insect defoliation (Swank et al. 1981, Eshleman 2000), 2) human population and development (Castro et al. 2001, and Boyer et al. 2002), 3) agriculture **(**Jordan et al. 2003**)**, 4) atmospheric deposition and combined effects leading to nitrogen saturation of forests **(**Aber et al. 1998, Aber et al. 2004**)** are well documented and reasonably well understood. In the northeastern U.S., agriculture generally contributes about half of the input of N to watersheds (via fertilizer, feed and N-fixing crops), while food imports for human population contribute roughly 15%, atmospheric deposition 30% and N fixation in forests 5% (Boyer et al 2002). These proportions vary as watersheds differ in their relative amounts of agricultural, developed and forested lands. Nitrogen exports generally increase with increasing inputs to agricultural lands (Jordan et al. 2003), but not necessarily so with forested lands (Goodale et al. 2002).

The ability of forested watersheds to retain the majority of N that is input via atmospheric deposition is an area of active research. Currently it is thought that N is rapidly bound up and retained by abiotic processes in soils, slowly released into available N pools and then taken up for plant growth (Aber et al. 2004, Goodale et al. 2002, Currie et al. 2004**)**. This potential abiotic functional role of soils as beneficial to the living community in the acquisition, storage, release and buffering of a key limiting nutrient is important for several reasons. Since soils are strongly modified by the living community, but indirectly via excretion, death and organic matter (i.e., as side-effects of direct actions of living), the benefits of soils suggest that the side-effects or unintended consequences of living communities on their local environments are generally beneficial. These recent results are compatible with other work that describes the feedbacks between and co-evolution of living communities and soils as beneficial to living systems (van Breemen 1993, Lovelock 1993, Eagleson 1982).

Existing understanding and proposed solution of excess N loading lead to management recommendations that focus largely on quantitative issues such as 1) efficiency of N use and 2) reduction of N emissions and resulting atmospheric deposition.

A few studies suggest more fundamental, qualitative reforms such as reorganizing human networks of N flux such that N is recycled from social and economic realms back onto agricultural lands (Cowling et al. 2001). A major policy and management approach is to determine and enforce a total maximum daily load (TMDL) for many individual water constituents such as N, P and sediment for individual rivers such as the Patuxent (Fisher et al. 2005). More participatory and less regulatory approaches include tributary strategies and tributary teams that work together to develop targets for water quality and restoration (For example see http://www.dnr.state.md.us/bay/tribstrat/).

Knowledge Gaps and New Questions

In summary of current knowledge in terms of the environmental science of excess N export, as a type case example of systemic human-environmental problems, it is commonly known that agricultural and other human land uses export more N than forested and other natural lands. However, it does not seem well understood 1) whether, and if so why, this is *always* so in terms of ecosystem structure, organization, function and dynamics, 2) whether the short-term environmental problems of excess N export and related problems such as soil loss can be fixed, restored, substituted for or ignored in the long-term and relative to short-term gains in production and profit (i.e., are conventional agriculture, environmentally unsustainable housing, industry or science net “good” solutions or net “bad” problems for society?), and 3) whether there is an alternative ecosystem configuration that could provide needed ecosystem services such as food and fiber (or housing, industry, science) while also retaining nitrogen and building soils, and thus serving to preserve and enhance water quality, as forests do.

In other words, should we look for management solutions such as improving efficiency of our current systems, or do we need to think of more fundamental changes in direction or paradigm such as total redesign of systems to improve effectiveness, or both? Solutions to individual problems such as excess N that do not create other potentially worse problems elsewhere are also needed. To improve the N situation by increasing use of fossil fuel dependent technology, for example, does not serve to solve the general human-environment problem of unsustainability as a whole.

In terms of the best ecological strategy or organizational form for environmental science itself, two general camps now suggest qualitatively different approaches. A majority of environmental science institutions assert via their actions that environmental sustainability of their own operations is not an important issue. A small minority asserts via their actions and explicitly stated goals that environmental sustainability of their own operations is of fundamental importance to their core missions of research, education and public service. The author is not aware of studies that have compared and contrasted these two competing strategies relative to the long-term success of environmental science.

Switching back to the closely related issue of energy, we may consider Hubbert's (1976) three general scenarios for the future. The first is the case that we find ways to sustain or increase our energy use. This might occur if fusion or cold fusion is achieved, for example. A second scenario on the other extreme is that we revert back to a much lower energy basis like natural communities that run on solar energy. A middle scenario would put our long-term energy capacity somewhere in between. Designs for sustainable systems to operate with such a moderate level of energy use might be achieved from the top down - by changing designs of our current systems to use less energy - or from the bottom up – by augmenting the designs of natural systems to increase energy capacity in ways that are sustainable and preserve long-term productive capacity. Whether the bottom-up or top-down direction is better, or how to combine them, seem important open questions.

In order to integrate several complementary perspectives and to address core questions such as the best ecological strategy and organizational form for human systems in general and for environmental science in specific, reports on three research projects follow this chapter.

The first project was a field and laboratory study to compare the qualitative effects manifesting from the ecological strategies or organization forms of a *human regime* and a *natural regime* as exemplified by long-term agriculture and long-term forests, respectively. This work explored total soil storage of C, N and organic matter and the vertical profile or depth distributions of C, N and organic matter.

The second project examined environmental science as an ecological process to determine *How far are we from local environmental sustainability?* This project quantified 1) the energy, C, N and water demands and waste emissions of environmental science, 2) the local, natural, ambient supplies of energy, C, N and water and waste absorbing capacities, and 3) the gap between these two both as absolute numbers and as relative rates. Thus this study estimated the local ecological carrying capacity (in terms of four key natural resources) required to do environmental science and assessed whether the science operation examined operates within that carrying capacity.

The third project attempted to depict the necessary and sufficient conditions for (models of) environmentally sustainable systems. In essence, the question posed here was *Whether or not, and if so why, the human regime always fails (results in tragedy of the commons) and the natural regime always succeeds (results in bounty of the commons) in terms of environmental sustainability?* In reference to the main overall question addressed then (What is the best ecological strategy?) this sub-project sought to answer the question with a category or class of strategies, organizational forms or regimes (given a specific constraint – the best ecological strategy for long-term, local environmental sustainability.) For example, two basic classes of organizational forms were compared: systems with predominantly 1) linear and one-way material flow, such as human industrial and conventional agricultural systems and those with 2) cyclic and two-way material flow, such as forests.

The following major questions are addressed in the three research projects:

1. What is the best ecological strategy or ecological organizational form for coupled human-environment systems for long-term environmental sustainability and health (i.e., freedom from chronic, systemic problems such as excess N loading, excess CO_2 emissions, etc.)?

2. What are the necessary and sufficient characteristics of environmentally sustainable systems (or at least for models of such systems)?

3. What qualitative differences most strongly distinguish unsustainable human (e.g., conventional agriculture) from sustainable natural (e.g., forest) regimes or ecological organizational forms?

4. What is the best ecological strategy or organizational form for long-term operation and ultimate success of environmental science itself?

5. How far from local environmental sustainability does environmental science now operate? What reductions would be needed to become locally, environmentally sustainable?

6. What would locally, environmentally sustainable science be like in terms of energy, C, N, and water demands as met by local supplies and waste emissions met by local assimilative capacities? What is the local carrying or production capacity for environmental science?

7. Can sustainable ends in the long-term be achieved by unsustainable means and operations in the short-term? How do the long and short terms relate and interact? Can an end goal of high N retention be achieved via a science process with high N export?

8. Would locally, environmentally sustainable science be better or worse in terms of core missions of research, education, public service, and applications to management, policy and problem solving?

9. Is it better to internalize or externalize environmental costs of doing environmental science? What are the pros and cons, costs and benefits of these two options for environmental “capital accounting”?

10. Why do human systems as currently configured always fail (degrade environment or commons) and natural systems always succeed (enhance environment or commons)?

11. Are there alternatives that can “do both” – produce needed goods and services and improve the capacity for future production as they produce?

12. Are the short term costs of environmental and life support capacity worth it in the long-term? When are actions good or bad, solution or problem on balance?

13. Is there any pursuit or gain more important than maintenance of environmental life support?

While this last question may seem rhetorical in a facetious way, the author can in fact conceive of several useful affirmative answers. Colonization of life into new areas, facilitating emergence of new life forms and quality of life, for example, are three pursuits that might at times be more important than sustaining or continuing life as it is.

Systems Organizational Types and Their Dynamics

Even if, as discussed above, natural ecosystems like forests provide available, testable and replicable role models for effective and sustainable human life support, it would also be useful to understand the exceptions to the “ design rules” or systems design principles these long-lived systems employ to achieve sustainability. That is, *Is there a fundamental systems analogue or systems archetype of existing, conventional agriculture and other human systems that are inherently <u>ineffective</u> and <u>unsustainable</u>?* The working hypothesis here is that humans have developed agriculture, urban/suburban development and nearly all other projects that impact the environment using systems analogues of either 1) an organism or 2) a machine or linear control system.

To determine the formal, topological, systemic or relational requirements for both sustainable (i.e., living communities, ecosystems, biosphere) and unsustainable (i.e., machines, heterotrophic and perhaps all organisms in isolation, conventional agriculture) processes would help us to know when long term success is impossible for whole categories of fundamental systems designs. If the root cause of human-environment dysfunction and degradation of our own life support basis is due to transference or application of an inappropriate systems analogue or metaphor, then correction of this metaphorical or mental mistake could conceivably lead to holistic and lasting solutions to our current environmental “mess”.

While it may be that certain material substances, technologies or methods are substitutable (i.e., replacements for materials or fuels can be found if existing ones run out), a working view here is that *certain fundamental relations are not substitutable* – with them systems can be sustainable, without them systems cannot possibly be sustainable. This work is the search for the concise characterization of these hypothetical generic and necessary relations. Even if one assumes or hopes that future technologies, fuels or systems designs will lead to solutions, it seems that any new technologies will likewise need to abide by certain qualitative formal properties such as 1) renewable, net energy, 2) recycling materials processes and 3) the mutually reinforcing interdependence of these two properties. The process to develop and test the hypothesis of such necessary and sufficient relations will also include attempts to falsify this hypothesis or find the exceptions to such rules.

An individual factor is *necessary* if it cannot be removed from a model or formalism without loss of a required or desired whole-system function. A set of factors is necessary if none can be removed or lost, i.e. there are no extra, superfluous or unnecessary factors included. A set of factors is *sufficient* if nothing else is needed to produce the desired function. Similarly, a sufficient set of factors ought to leave no room for any conceivable factors that would improve substantially the desired/required whole-system function.

This approach seeks first to define which options, outcomes and whole-system functions are *effective*, which is ostensibly more important than and logically prior to *efficiency*. To increase the efficiency of a process that is not effective would not necessarily lead to overall progress or improvement. Such effort could actually serve to make a bad thing more efficient at being bad! Only if we have determined and are confident in the effectiveness of an action does it make sense to work to increase efficiency. Efficiency can be nearly equally critical however – below a certain threshold of efficiency, a given process may cease to be effective. The interplay of effectiveness and efficiency is more complex given multiple needs for living processes and communities. Multiple needs and challenges suggest a hierarchy of living system and community needs similar to Maslow’s hierarchy of needs in his psychology of human motivation (Maslow 1943).

In Figures 1.2 and 1.3 are contrasted working, hypothetical and exaggerated system models for forest versus human agricultural system. These hand-drawn sketches depict some of the main links to be tested between qualitatively different network configurations and qualitatively different time dynamics. The qualitatively different internal system configurations are circular (natural, forest, sustainable, autocatalytic, Figure 1.2A) versus linear (human, agriculture or developed, unsustainable, liquidating, Figure 1.3A). This distinction comes from early identification of the importance of circular causality (Hutchinson 1948) as well as recent work on the special properties of autocatalytic loops (Ulanowicz 1997, Letelier 2005). Hypothetical and qualitatively different time dynamics are shown for growth and development of sustained production (new biomass or carbon, nitrogen or energy input) and long-term productive capacity with a natural overshoot (Figure 1.2B) versus liquidation of a finite resource and the boom and bust, total collapse cycle with no long-term production or productive capacity (Figure 1.3B). Also shown are qualitatively different time dynamics for nitrogen export, with sustainable systems being resilient to rare and one-time disturbances and able to retain most nitrogen (Figure 1.2C) while unsustainable systems are continually disturbed (soil tillage, crop harvest, N fertilizer inputs, etc.) and export large amounts of nitrogen in chronic signal of poor system health (Figure 1.3C).

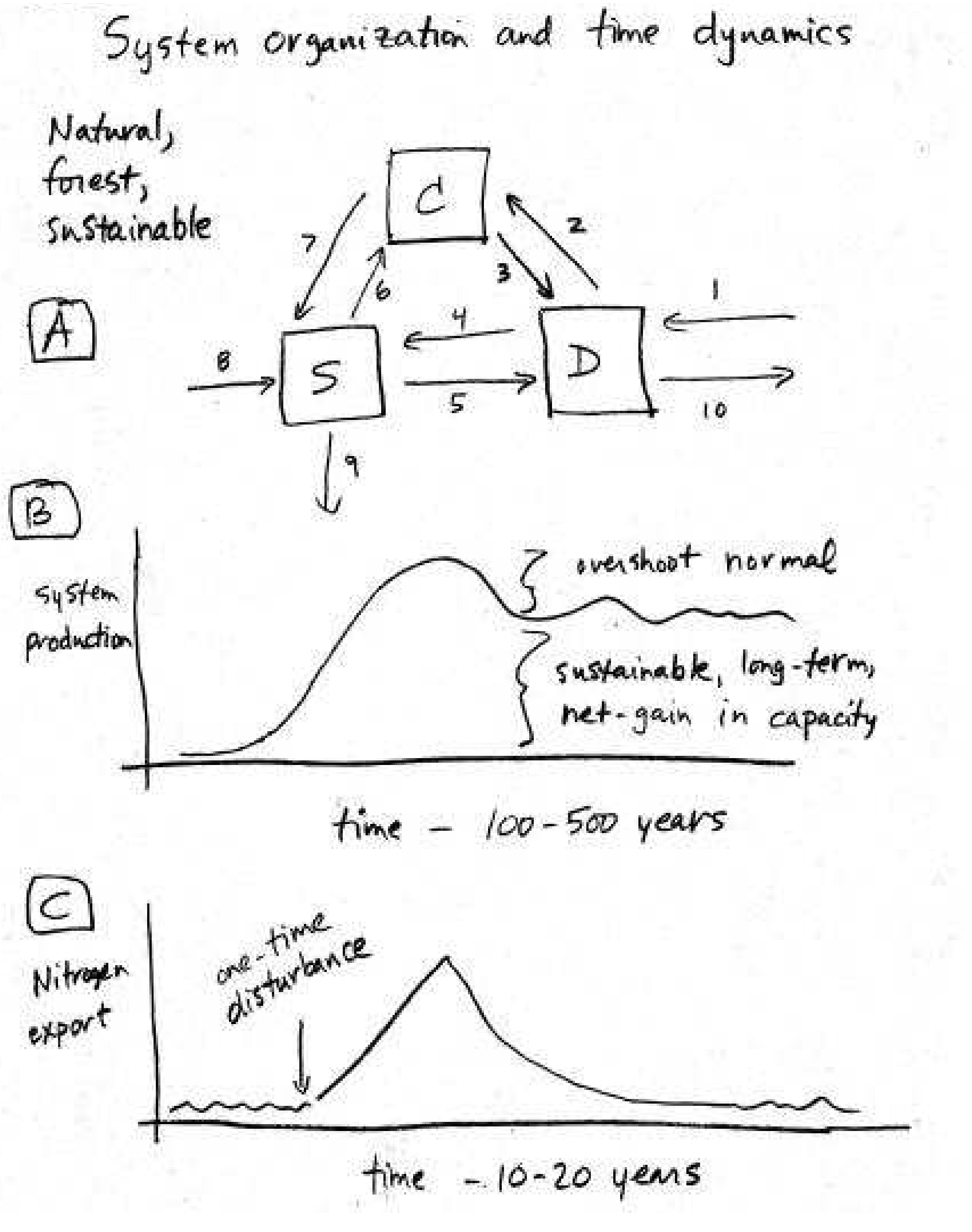


Figure 1.2. A. Forest system network organizational form with autocatalytic loops and high recycling. Components are labeled C for composers (i.e., autotrophs), D for decomposers and S for soils. B. Hypothetical time dynamics of production, productive capacity or system assets. C. Low nitrogen export under normal conditions and resilient recovery of N retention following disturbance.

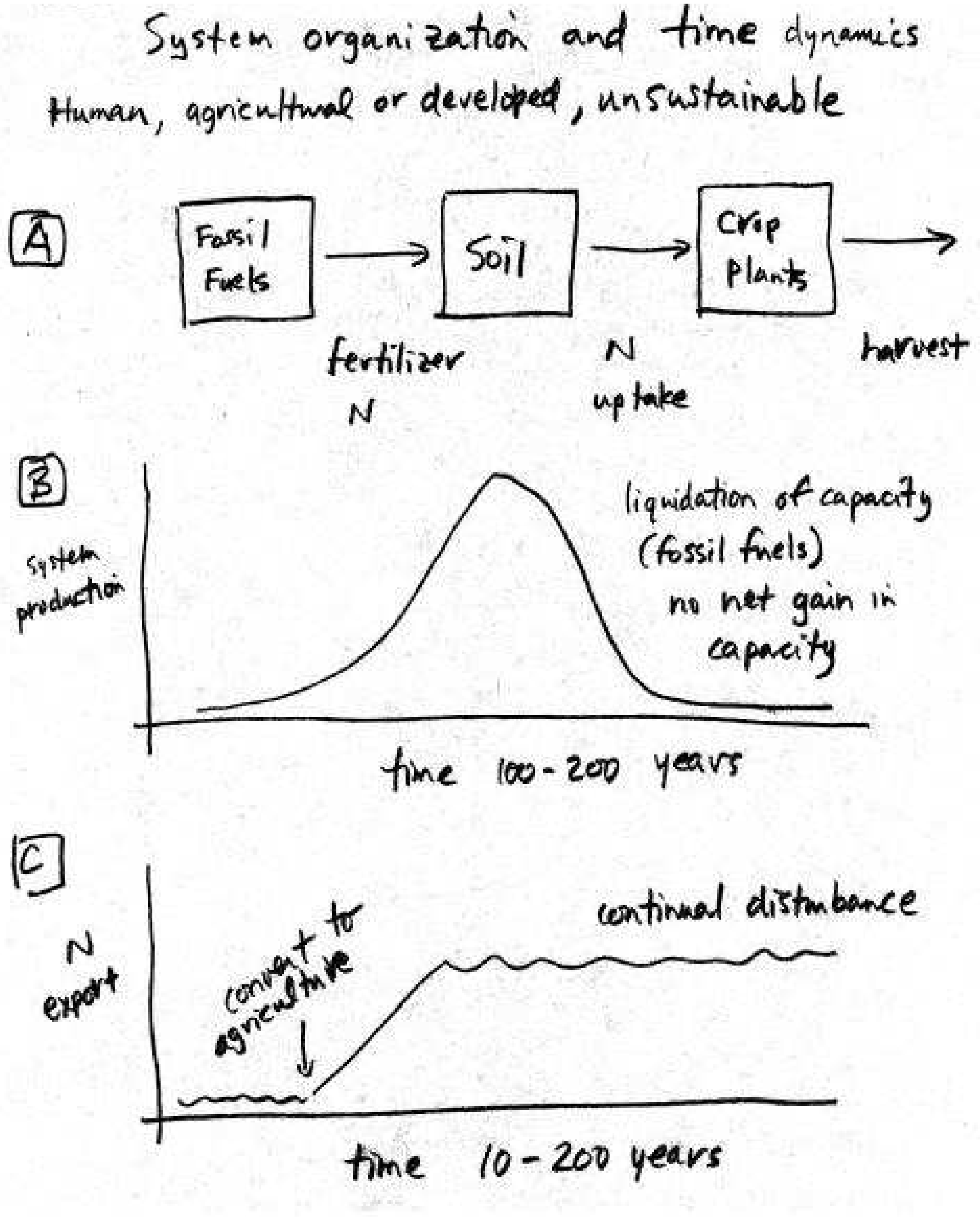


Figure 1.3. A. Human system network organizational form with predominantly linear flow through and low recycling. B. Hypothetical time dynamics of production, productive capacity or system assets showing liquidation. C. Low nitrogen export under pre-conversion, forested conditions and resistant persistence of high N export during chronic disturbance.

Work and concepts from two related areas inspired this research. Systems archetypes (Senge 1990, Wolstenholme 2003**,** Sweeney and Meadows 1995) have been developed as approaches to managing complexity in business and other sectors. These are considered to be generic structures that strongly influence dynamic behavior over time. Systems archetypes involve the interaction of two main causal loops – one for intended consequences and one for unintended consequences – and two main types of causal loops – reinforcing and balancing. Systems archetypes describe recurring patterns in and recurring relations between structure and dynamics such as that seen in the tragedy of the commons (Hardin 1968).

The comparative modeling science approach was also informed by complexity theory. Complexity is the concept that meaningful representation of most (if not all) natural systems requires more than one model or perspective (Rosen 1991, Giampietro 2004). The opposite property – simplicity – is logically then a system or representation that requires only a single model or involves only a single variable to be optimized. Utilizing multiple and complementary approaches was the main means of acknowledging this view of complexity.

An emerging and related area of potential significance is impredicative logic (Giampietro 2004, Kercel 2003). Impredicative loops are closed causal loops that are also multi-level or hierarchical. Studies in impredicative logic have led to new math for sets (Barwise and Moss 2004) and it seems to be compatible with autocatalytic loops in ecological systems (Ulanowicz 1997). A popular book that treated related topics using the terminology of "strange loops" is Hofstadter's (1979) Godel, Escher, Bach.

Network analysis, using information theory and Bayesian approaches (Ulanowicz 1986), was the main method in the third comparative food webs project. The holistic principles and paradigm of ecological network analysis also inspired and guided all the projects. One pivotal and parsimonious model borrowed was the three-component autocatalytic loop of Ulanowicz (1997). This model was modified slightly to include an abiotic environmental component with an integral and functional role. Thus a carbon network "kernel" (Figure 1.4) and a basic nitrogen network kernel (Figure 1.5) can serve to represent minimal systems able to exhibit the autocatalysis and indirect mutualism shown to be key to non-mechanistic aspects of ecosystem dynamics (Ulanowicz 1997). These diagrams and fluxes are drawn for forest systems, but they could potentially be the basis for quantifying minimal sustainable agricultural or sustainable human systems as well.

New Directions and New Foundations for Environmental Science

It may be common for people to enter the field of environmental science from a desire to help and to serve by working to solve pollution, species loss and other environmental problems. People that designed the welfare system of public assistance and other similar government programs similarly sought to help others and alleviate the problems of poverty and hunger. But public assistance given in the form of material, food or financial subsidies also created dependencies – the unintended consequence of seeking to help others directly often led to a weakening of people's capacities to help themselves, and generations of families came to know themselves as, and expected to remain, “welfare families”. Similarly, unless we address both the long-term and unintended consequences of environmental science, we run the risk of creating new and perhaps worse human-environment problems. By daily running our science institutions, labs and classrooms in ways that *scream* that energy, carbon, nitrogen and water fluxes, stores and

Detailed Captions for Network Kernel Figures, Figures 1.4 and 1.5, that follow.

Figure 1.4. Carbon network kernel. Basic schematic of a minimal carbon network able to demonstrate autocatalysis and self-organization. C = composers or autotrophs (e.g., forest trees, shrubs, herbs or agricultural crop plants), D = decomposers or heterotrophs (e.g., forest soil microbes and insect herbivores and agricultural soil microbes, insects, livestock) and S = soils. The numbered fluxes correspond to:

1. Carbon fixation by plants, gross photosynthesis
2. Autotrophic respiration
3. Heterotrophic consumption, herbivory, parasites on plants
4. Local CO_2 recycle from heterotrophic respiration
5. Decomposition of soil organic matter by heterotrophs
6. Death, litter, excretion by heterotrophs to soil
7. Heterotrophic respiration
8. Plant litter, exudates, organic C to soil
9. Soil loss of C via leaching, erosion, etc.
10. Weathering of carbonate rocks

Figure 1.5. Nitrogen network kernel. Basic schematic of a minimal nitrogen network able to demonstrate autocatalysis and self-organization. C, D, and S as in Figure 1.4. The numbered fluxes correspond to:

1. N_2 fixation by microbes
2. N uptake by plants via direct symbiotic association
3. Heterotrophic consumption, herbivory, parasites on plants
4. Death, litter, excretion by heterotrophs to soil
5. Decomposition of soil organic matter and uptake of inorganic N by heterotrophs or microbes
6. Plant uptake of soil solution inorganic N
7. Plant litter, exudates, organic N to soil
8. Atmospheric and other N deposition or import to soil
9. DON, DIN leaching, organic matter erosion from soil
10. Microbial denitrification to N_2 and other gas emission

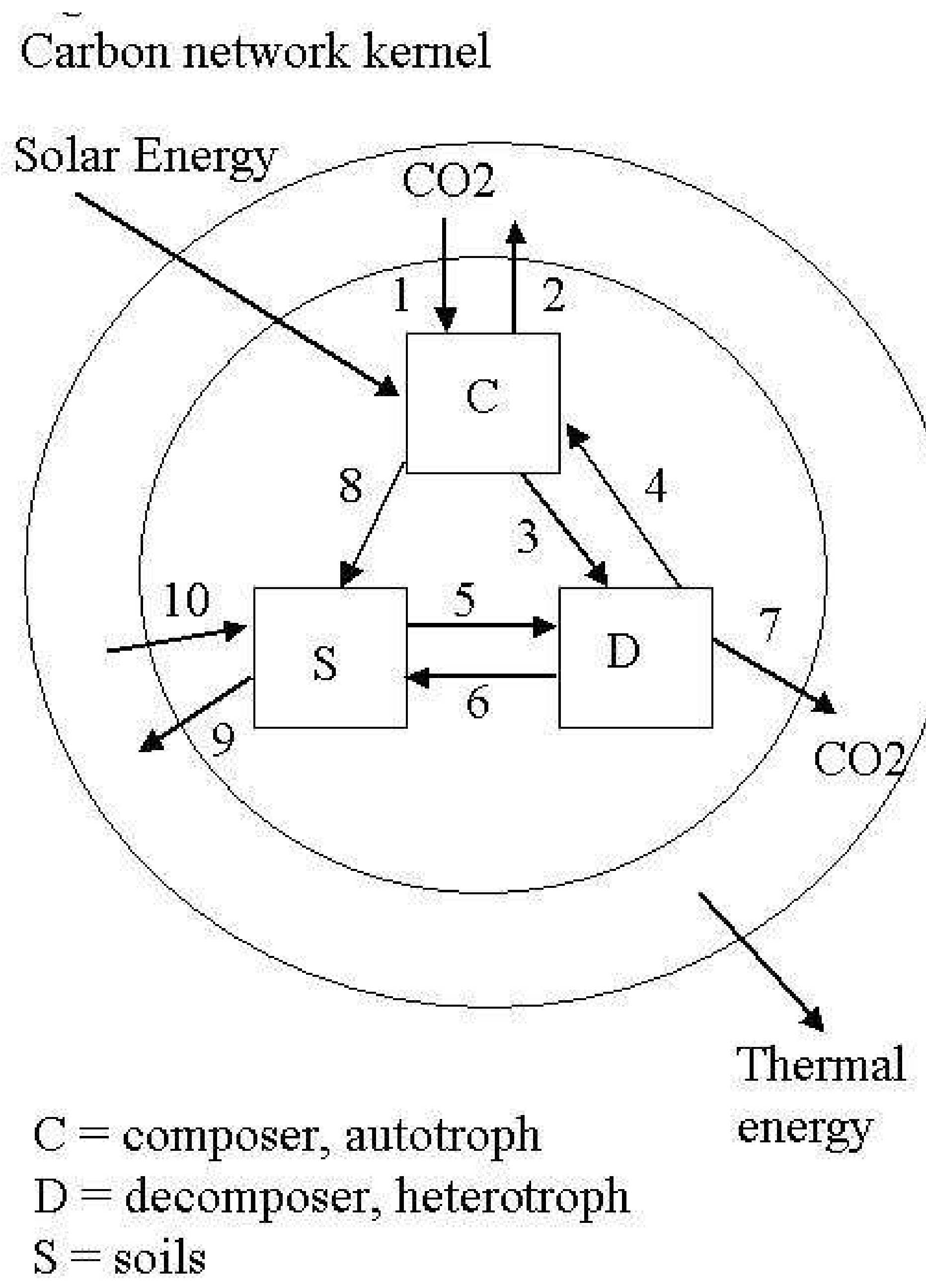


Figure 1.4. Minimal carbon network. See detailed description of components and fluxes on previous page.

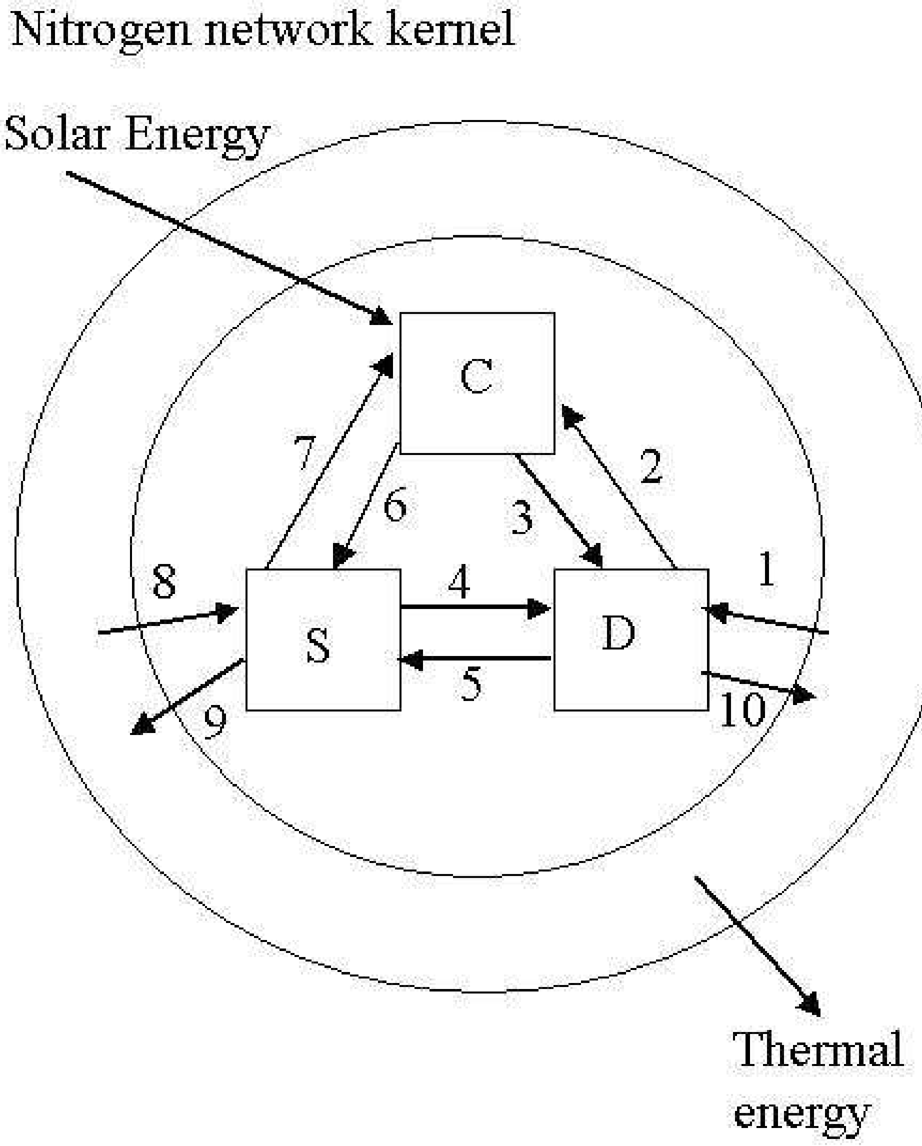


Figure 1.5. Minimal nitrogen network. See detailed description of components and fluxes on page before Figure 1.4.

input and waste capacities are not important considerations, we may inadvertently teach deeper and longer-lasting lessons than our research and lectures that *whisper* wishful words about human sustainability.

Paradoxically, the proposed research may lead to realization that our seemingly unsustainable, consumptive ways are helping, in a manner of thinking. But the forms of "assistance" we provide to others in future times or in distant places may not be of the form that we currently imagine. If we are not in general sustaining, we may instead be colonizing or pioneering. If we are not passing on a way of life that works and can last long term, we may be paving the way (literally and figuratively!) for a new way of life that can, or must, come after. By depleting the majority of high quality energy and material forms now, we in a way create the "necessity" that could be "the mother of invention" for future generations who will have no choice but to use, consume and pollute less and to conserve and recycle more. If we are the r-selected, individualistic, growth-minded form of Homo sapiens, we are preparing an environment that may facilitate the arising of a K-selected, community oriented, conservation-minded next wave of our species. These metaphors apply not only to people in general, but also to people in science, as science so far appears no more sustainable than any other sector of culture. Unfortunately for our legacy, this kind of "helping" is not likely to be seen as such by future generations. Such "retrospective forecasts" go back a long way; here is a classic version of it by one of the pioneers of ecological modeling, Alfred Lotka (1925, p. 279):

> The human species, considered in broad perspective, as a unit including its economic and industrial accessories, has swiftly and radically changed its character in the epoch in which our life has been laid. In this sense we are far

> removed from equilibrium – a fact which is of the highest practical significance, since it implies that a period of adjustment to equilibrium conditions lies before us, and he would be an extreme optimist who should expect that such adjustment can be reached without labor and travail. We can only hope that our race may be spared a decline as precipitous as is the upward slope along which we have been carried, heedless, for the most part, both of our privileges and of the threatened privation ahead. While such sudden decline might, from a detached standpoint, appear as in accord with the eternal equities, since previous gains would in cold terms balance the losses, yet it would be felt as a superlative catastrophy [his spelling]. Our descendants, if such as this should be their fate, will see poor compensation for *their* ills in the fact that *we* did live in abundance and luxury.

Whether considered good, bad or neutral, it seems important to clarify what is going on in this time of great changes.

A clarified mythology, group story or cultural narrative by which we could alleviate any hidden guilt and harness more positive empowerment for change could aid the coherence and coordination necessary for community organizing that now seems required on almost all scales from the individual to the global. Such clarification of what is really going on, what are the real and long-term consequences and legacies of our current actions in science and society, might also open up new avenues of thought and action. If we could get clear that sustaining is not the same as, is diametrically opposed to, colonizing or pioneering (and concepts like r-selection and K-selection and all of ecology apply to humans as with other organisms, species and populations), it might enable and inspire us to ask *What kind of narrative might reconcile the seemingly opposite tendencies of sustaining and colonizing?* One option is that the rich, educated, technologically advanced folks in the West and North might decide to reverse direction completely for the greater good. Instead of exponential growth in energy use and materials consumption and waste, a movement could arise for *exponential decreases* in these physical impacts. Such radical change might be accompanied by an exponential growth in spiritual, social, family, relationship and other non-material forms of activity and impact. Such action could quite literally be part of an effort to “save the world”, since freeing up life support capacity could make the difference between mass population crash and some less catastrophic “soft landing” or “prosperous way down” (Odum and Odum 2001).

Many in the pro-environment social action camp seem to assume that colonizing and exploitation of natural resources is necessarily, ever and always, bad. Yet colonizing, pioneering and resource exploitation are ubiquitous in living systems at different stages. Another idea for a story in which these two potential conflicting tendencies might achieve synergy is in space exploration and colonization. Neither mode alone could achieve a self-sustaining colony – not an oxymoron! – off-Earth. Only in cooperation could both sustainability-minded and colonizing-minded humans, as interdependent participants of a whole and closed community-ecosystem in a spacecraft, space station or extra-terrestrial colony, achieve independence from Earth.

The two modes are potentially synergistic in conscious cooperation of a great challenge like extending Earthlife into space. Right now, in unconscious competition, the two modes are antagonistic and the fight seems a key human aspect of the human-environment problem. Quinn (1996) talks of two types of people, the “leavers” who leave most environmental resources as they are, and the “takers”, who take all they can get. Another but perhaps more harmonious simple dichotomy in human-environment relation might be to consider a conscious bifurcation soon to come between the “leavers” who choose leave Earth to continue the colonizing mode and the “stayers” who vote to stay on Earth and work to switch social and economic priorities toward sustaining life here. If these modes are in fact fundamental and inseparable in dialectic or complementary fashion, the story would go that each group would realize they needed some members from the other group to succeed in their mission.

If we do want to have some certainty or confidence that we are in fact helping and serving others, that what we are doing now fits into and contributes positively to dynamics on a larger level, we may need to initiate a widespread, in-depth and sustained dialogue within environmental science that addresses not only our knowledge and discovery products but also the biophysical capacity and basis by which those products are created. That is, for knowledge, techniques, creations or innovations to be lasting, we likely will need to ensure that the environmental context in which that knowledge is meaningful, or those innovations operate, lasts as well. Such a conversation within environmental science would address such questions as raised here, like *Can we lead the public to sustainability and environmental health by non-example or counter example, or must we lead by positive and actual example?*

Another way to put the work here into context is to consider the "ecological metaphysic" of Ulanowicz (1999):

> If one wishes to understand the development of biological systems in full hierarchical detail and is not content with the abrupt juxtaposition of pure stochasticity and determinism found in neo-Darwinism (Ulanowicz 1997), then one must abandon the assumptions of closure, determinism, universality, reversibility and atomism and replace them by the ideas of openness, contingency, granularity, historicity and organicism, respectively. That is, one must formulate a new metaphysic for how to view living phenomena.

Ulanowicz (1999) proposes five main concepts that differentiate the Newtonian, mechanistic metaphysic of mainstream science from an ecological metaphysic that he suggests would enable full understanding of living systems. He makes a compelling case for the necessity of five principles as foundations to the practice of ecology. (His framework now is based on three principles (Ulanowicz in preparation), but the prior form is addressed here.) His *openness* refers to ontic or causal openness and suggests that chance is real and active, not merely a source of “noise” or “error”, and thus not all is determined or determinable. His *contingency* relates to that qualified answer so often heard in ecology, “it depends…”. Most if not all events arising from cause-effect relations are not static but are contingent on other outcomes, relations and the context in which they occur. *Granularity* is his antidote to unrestrained universalizing. A granular extent to a science law, model or principle would admit limits to domains of applicability, would seek to “renormalize” or reconsider frames of reference in vastly different systems, and would be compatible with locally unique forms of place-based science institutions as suggested for locally environmentally sustainable science. *Historicity* is irreversibility and the importance of the time course of events – what happens and when it happens both matter, and many processes show hysteresis and do not run the same way backward as forward (e.g., soil wetting versus drying). *Organicism* is the operating assumption of unfractionability and wholeness of living systems, the opposite of or counterbalance to reductionism. This first principle of an ecological metaphysic might be paraphrased as “Systems do not consist of parts within wholes, but of wholes within wholes” (Senge 1990).

Based on the present work, two new principles are suggested for addition to these five. These two candidate first principles seek to help ground the ecological metaphysic of Ulanowicz in a real and lasting biophysical basis or capacity to do science. These principles are 1) *self-reference* as shown in the need for biophysical, ecological self-examination of science and potentially in the need to internalize environmental costs and 2) *sustainability* as in attention to and regeneration of long-term, local environmental capacity to do science. Both of these concepts seek to ground or connect science to real environmental contexts. And as these contexts vary from place to place they suggest that the realizations or embodiments of science ought always to vary with the environment as well, just as we expect and observe natural systems to do. In a way, both of these concepts as combined with the original five seek to help environmental science "come to life" or "take on a life of its own". That is, it may be that the best form of life science for understanding life and solving problems of life is a science that is itself very much alive. "Alive" is used here as associated with following the same ecological strategy and organizational form of natural systems like forests that differ greatly between boreal, temperate and tropical contexts, yet all manage the same apparent life "magic" (Corning 2003) like trick of improving their environments as they live.

Summary and Conclusions

Another form of a main question here is: *If we account for our own C, N, water and energy processes do we find that environmental science is as much part of the problem as any other sector of society? And if we are part of the problem, does this not suggest that we are not really objective relative to the problem?* Rather than being independent, external observers of the excess N and other unsustainable human-environment problems, we may instead be interdependent, internal participants in those problems and their systems contexts. If so, it seems important to explore what this implies and what kind of science can provide meaningful knowledge without the assumption or need for objectivity. Internalism (Salthe 2001) is a realm of study that may become highly relevant for such explorations in cases where science seems inextricably "on the inside" of its systems of study. Adding internalism to science at the mesoscale – time and space scales near the order of human size and lifespan – could provide an important third scale where internalism is integral to science. It is already known to be important at the extreme microscale (quantum physics, observers entangled with experiments, Heisenberg uncertainty, etc.) and the extreme macroscale (astrophysics and cosmology, observers are inside all systems of study). The imperative of internalism at scales in the middle, where all human scientists are entangled via biogeochemical fluxes and life support relations with any Earth system they study, could elevate internalism to equal standing with objectivism in terms of its general necessity for valid science.

One intended and hoped for novel insight from the self-examination study is that we may see that the same ecological and environmental issues, challenges, strategies and organizing principles that we have studied and learned to be fundamental in communities in the natural world apply fully to ourselves as well. Bill Mollison, creator of the permaculture approach to reorganizing human actions to work in cooperation with nature, describes a mental shift that can occur via such self-reflexive application of science to one's own life, behavior and reality:

> When the idea of permaculture came to me, it was like a shift in the brain, and suddenly I couldn't write it down fast enough. Once you've said to yourself, 'But I'm not using my physics in my *house'*, or 'I'm not using my ecology in my *garden*, I've never applied it to what *I do*,' it's like something *physical* moves inside your brain. Suddenly you say, 'If I *did* apply what I know to how I live, that would be miraculous!' Then the whole thing unrolls like one great carpet. Undo one knot, and the whole thing just rolls downhill" (AtKisson, 1991).

It may have seemed in modern times as if the energy and material requirements of existence could be ignored and all focus shifted to “survival” and competition in economic and social arenas. But comparative ecosystem studies combined with ecological self-study may confirm the view held by many that our current energy and materials supply system is almost completely dependent on an artificial and short-lived basis in the form of fossil fuels. Confirmation and acceptance of this crucial fact could further call into question whether achievements, research and management efforts in restoration, conservation, pollution control, invasive species and related areas must be redone and readdressed after a major “correction” or transition occurs during which human organizational forms, energy and materials processes are brought back into compatibility and sustainability with real environmental capacities. Thus success achieved in the unsustainable present period may not necessarily translate into success in some more sustainable future.

Qualitative, quantitative and comparative self-examination of environmental science may reveal that the root cause of the general human-environment problem, or excess N loading in specific, is not “out there”, as in a cause existing somewhere separate from humans and our individual and collective minds or intelligences. Self-reflexive research suggests that we may have to look no farther than ourselves to see and experience both the ultimate effects of these problems and the root causes. Similarly, this line of thought suggests that solutions are not likely to come from “out there”, as in from either 1) substitution of new energy or materials resources, or 2) technological devices or increases in efficiency of existing devices and machines. Instead, the route to lasting and effective solution may be one that leads inward, and the novelty, innovation and new creations that are needed may be new constructs within the mind (or changes in heart or spirit, other key inner human realities). If we are to act like and achieve the elegant and excellent environmental successes of living communities such as forests we may first have to learn to “think like an ecosystem” (Tippett 2004). Such a collective intelligence (Wolpert and Tumer 2000) as a healthy social mental or knowledge capacity (i.e., wise and effective science) may be integral to and required for collective health or right organization of a social body as continually and well “fed” by necessary environmental materials such as energy, carbon, nitrogen and water.

If deemed successful and valid this research could indicate clear directions and guidance for how to convert existing unsustainable human systems to perform more like sustainable natural systems. Experience from physical hydrology projects by the Army Corps of Engineers (ACE) on the Kissimmee River above the Everglades in Florida and the Charles River above Boston (Keith Eshleman, personal communication) underscore the value of judiciously refraining from altering natural systems. In both these cases it seems the ACE determined that the natural patterns, structures and functions are “as good as it gets” for water supply and flood control and they recommended leaving the natural wetlands alone on the Charles and restoring meanders on the Kissimmee. “Kenosis” or letting go of control (Ulanowicz, personal communication) may often be integral to a comprehensive, holistic “system of solutions” to correct our unsustainable “system of problems” with the environment.

Similar success may be gained from this general approach to follow the lead of natural systems and it may help us solve our excess N and energy problems as well as water problems. Such general, theoretical results from modeling can be linked to specific, applied options such as permaculture (Mollison 1996) – agriculture and other land cover that is perennial and managed without major soil disturbance (as opposed to annual plants and soil tillage). Such reorganized agriculture is being developed in the U.S. mid-west using prairies (Jackson 1994) as the model and has also been suggested for Appalachia using forests as the model (nut and fruit trees combined with consumers like hogs; Salstrom 1994). This approach is called “biomimicry” (for example, see Biomimicry.org) in some circles and it seems corroborated by lessons from many cases.

Permaculture, biomimicry, organic agriculture, the “organic architecture” or Frank Lloyd Wright and the approach proposed here (organic science?) may all differ subtly but significantly from allied fields such as ecological engineering and living machines (Kangas 2004). Many compatibilities exist, such as 1) identification of the local “energy signature” as necessary for sustainable solutions, and 2) allowing human-created systems to self-organize and self-modify. But where ecological engineering and similar approaches seek to “use ecological processes”, living organisms or living communities to solve human problems, the kenotic or perhaps slightly softer path would balance this intention with a willingness for human participants to “be used” to perform some valuable ecological function for the community as well. The principles espoused here would suggest that for living machines (or any machines) to be sustainable and viable long-term, systems would potentially need to incorporate “anti-machines” to generate or harness compensating capacities to repair the dissipative actions of the machines and allow operation at break-even or better in terms of biophysical capacity.

Currently, most people don’t seem to think that ecology and biophysical limits apply to humans – not even ecologists and environmental scientists! Most people also seem to think primarily about short-term issues, except perhaps for retirement planning and financial legacies for heirs. People also seem to think from the perspective of organisms or utilize generic system metaphors of organisms or machines only. The present work seeks new ideas, models and metaphors by which humans can think better, be wiser and have better long-term success in our environmental relations. Sustainability, human ecology, long-term views and explicit accounting of environmental capacity invert conventional wisdom and provide hypothetically better wisdom that one day may become conventional.

By more explicit, quantitative and rigorous modeling exercises, we may get more concrete information to help us decide whether we are in fact moving forward in progress or backwards in problems when we continue to degrade environmental life support during other pursuits such as agriculture, industry, housing and environmental science. If many people incorrectly hold the view that current system configurations are working well, it would be important to point out the fallacy in this assumption. By comparative ecosystem studies and exploring general models it may also become apparent that we do in fact have alternatives, that systems organizations exist from which we could borrow principles to reorganize our own systems. Showing that these sustainable system designs correlate with and can be used to generate positive dynamics and trends in productive capacity over time could add weight to efforts to promote them as roadmaps for changing human systems. Dispelling these two potential misperceptions – that what we are now doing is successful in the long-term, and that we have no other options but systems configurations and action patterns that degrade the environment – could increase the interest in and collective will to pursue more sustainable human-environment relations.

A last comment comes from David Orr who has suggested that our current environmental crisis, its cause and solutions are issues of the human mind, individually and collectively. Orr (1994) wrote, "The planetary emergency unfolding around us is . . . a crisis of thought, values, perceptions, ideas, and judgments. In other words, it is a crisis of mind, which makes it a crisis of those institutions which purport to improve minds." In addition to suggesting that responsibility for solutions falls to universities and other institutions of learning, he suggests using our campuses and schools as laboratories for study, self-examination and learning through experience. Orr (1992) also wrote:

> Ecological education will, first, require the reintegration of experience into education, because experience is an indispensable ingredient of good thinking. One way to do this is to use the campus as a laboratory for the study of food, energy, materials, water, and waste flows. Research on the ecological impacts of a specific institution reduces the abstractness of complex issues to manageable dimensions, and it does so on a scale that lends itself to finding solutions, which is an antidote to the despair felt by students when they understand problems but are powerless to effect change.

This is an excellent summary of the main ideas and the outcomes hoped for from consideration of this research.

To focus on our own local ecology in environmental science first ought to lead to a more practical way to solve systemic environmental problems such as excess N loading to surface waters. If we can solve this and other energy, carbon and water problems in-house, the spreading of success stories and functional solutions ought to be much easier in comparison. The research reported here provides important information such as quantitative, physical goals for operations that would be sustainable within a local environment. Such local carrying capacity numbers ought to become as fundamental, common and often utilized a form of knowledge as one’s zip code, phone number or watershed of residence. Also crucial are the relational, qualitative organizational principles and resulting manifestations as characterized by the network structure and time dynamics of our own operations. Taken together, these descriptions of both the physical and organizational aspects of sustainable and healthy environmental systems hold promise to help us steer for where we need to go now, to make the major course correction strongly indicated by the rapidly accumulating signs that we cannot continue our current direction and trends. And if the projects here do not prove this, it is hoped they will at least increase the level of dialogue and contribute in meaningful ways to that dialogue.

Chapter 2

The Signature of Synergy in Soils With Potential Application to Solution of Systemic Environmental Problems

Introduction and Background

The same day as the writing of this paper exploring systemic causes and solutions to the general "humans in the environment problem", the Millenium Assessment (2005) was announced with these words:

> "Experts Warn Ecosystem Changes Will Continue to Worsen, Putting Global Development Goals At Risk.
>
> Wednesday, March 30, 2005. London, United Kingdom
>
> A landmark study released today reveals that approximately 60 percent of the ecosystem services that support life on Earth – such as fresh water, capture fisheries, air and water regulation, and the regulation of regional climate, natural hazards and pests – are being degraded or used unsustainably. Scientists warn that the harmful consequences of this degradation could grow significantly worse in the next 50 years."

Today's report echoes signals from the environment and warnings from scientists that have been coming for decades if not centuries. The "World Scientists Warning to Humanity" is another recent version of this general warning message of a fundamental problem with the way humans live in relation to our environment (UCS, 1992, Patten 1994). Alfred Lotka, a pioneer of ecological modeling, wrote of essentially the same matter in 1925 (Lotka 1925) and spoke of an "inevitable correction" by which the problem - seen by him as an imbalance - must be resolved with a return to balance as in steady state system behavior. The Millenium Assessment report calls for an increased pace in the changes needed to stop and reverse human degradation of Earth's ecosystems and our own life support system. One approach to accelerate change may come through looking deeply for the root causes of the general pattern of problematic relations between humans and our environment.

Within the field of ecology and environmental science, the author has participated in research projects seeking to understand human environmental problems in various specific configurations, mainly the problems of agroecosystem and soil health (Fiscus and Neher 2002, Fiscus 1997, Hess et al. 2000) and water quality related to excess nutrients running off from land to receiving waters such as the Patuxent Estuary and Chesapeake Bay (Eshleman et al. 2004, Eshleman et al. 2001). The intuition or general sense gleaned from study of these specific problems is that the root causes of the problems are *systemic*. "Systemic" is used to mean that the causes of the problems seem not to be isolated or localized in any one particular, separable or fractionable subset of the systems involved (e.g., agroecosystems, or watersheds coupled to estuaries). Instead, the causes of the problems seem to be spread or distributed over the whole of the systems involved. The systemic nature of the problems appears most directly related to how the systems are organized in terms of 1) internal or life-life relations, such as relations between organisms, individuals or general life forms, and 2) external or life-environment relations, such as relations between living organisms or whole communities and the environment. Other whole-system and relational approaches consistent with this idea that environmental problems and their causes are non-localized are the part-whole relation developed and explored in complex ecology (Patten and Jorgensen 1995) and ecological network analysis (Ulanowicz 1997) and the organic approach to ecology (Ulanowicz 2001).

A second sense of the root causes of human environmental problems is that the systemic causes are shared or common – a single systemic cause may be behind many specific instances of a general human-environment problem. Similarities in the specific instances of the problems – their contexts, onsets, symptoms and resistance to remediation - suggest a single, common, underlying cause. The potential good news here is that, if the hunch of a single common cause is correct, focused effort on that underlying cause could contribute to solutions in many different problem areas. This would aid the desire for rapid change to stop and reverse human degradation of the biosphere. The potential bad news is that a single systemic cause hints at some issue deep and fundamental in human nature itself (including science itself), one which may be difficult to face, admit, accept and change. The initial sketch of a solution offered here is founded on a new approach to ecological modeling within a new approach to environmental science. The whole-system perspective proposed also carries radical implications for fundamental change in environmental management and policy as well as human community and economic development practices.

To develop and test these abstract and intuitive hunches in more specific and tangible ways, fundamental and qualitative differences between two general living system configurations that seem opposite in their overall environmental outcome were explored – human-dominated versus natural communities, ecosystems or *regimes*. The term *regime* has the senses of 1) the form of organization and 2) the dominant principles of life-life and life-environment relation by which the community or ecosystem operates. The general conceptual model in mind was that operation under the human regime leads to a "tragedy of the commons" (Hardin 1968), while operation under the natural regime leads to a “bounty of the commons”. In Hardin’s (1968) classic on the “tragedy of the commons” he explains the tendency of human systems to degrade the local environment by the mismatch in costs and benefits of resource exploitation – while individuals gain from increased resource exploitation, the whole community shares the cost of this degradation. Thus for the individual operating with a competitive ethic, “looking out for number one” exclusively, the choice leading to personal advantage is always the same – add another animal to the herd, increase resource exploitation and resultant gains, let the community share the costs thus increasing overall profit or net gain. In short, under the human (free market, competitive) regime individuals win and the community commons lose in a zero sum game. The sense of inevitability around this story seems widely ingrained and accepted in Western industrial culture. Many, including the highest leaders in the USA, assume and act as if humans and our environment must be in conflict and that over-exploitation is to be treated as fully necessary and even associated with positive goals and progress. The refusal to participate in the Kyoto protocol on the grounds that it would “hurt the economy” is a prime example of the underlying assumption of win-lose relation between humans and the environment.

In seeming contradiction to this story of environmental tragedy, natural regimes such as forest ecosystems may represent a “bounty of the commons” such that both individuals (e.g., organisms, species) and the commons (e.g., community as a whole, soils, biodiversity, relationships) prosper. This seems paradoxical as ostensibly natural and human systems operate under the same kinds of evolutionary and competitive principles of interaction. In order to explore this hypothetical distinction between organizational or operating regimes and the hypothetical causal link to qualitatively different net environment outcomes (tragedy versus bounty), this research sought to determine if fundamental differences exist, and if so to describe and quantify those differences, between human-dominated and natural ecosystems.

From initial background knowledge, forest ecosystems seem to provide the ultimate role model for solving systemic human-environmental problems such as excess nitrogen (N), phosphorus (P) and sediment export from land to the Chesapeake Bay. Forest watersheds display impressive whole-system characteristics that seem an ideal model set for self-enhancement of environmental and water quality for which we might strive. Forests achieve 1) excellent water quality, 2) efficiency in maintaining water quality 2) internal regulation or self-control of water quality, 4) nutrient and sediment retention that is resilient to disturbance, 5) distributed, redundant and robust self-control of water quality, and 6) simultaneous achievement of other valuable environmental functions in addition to water quality (for more details on these six characteristics, see Chapter 1 in this dissertation).

To further explore the potential of forests as role models for human behavior, the present work compared 1) older, more natural forests, 2) younger, more managed (logged) forests and 3) long term agricultural fields. These three land use types might be considered to represent a gradient from less to more human domination. Similarly, old forest may be seen to have natural operation much greater than human-altered operation, logged forests have natural operation greater than or equal to human-altered operation, and agriculture has natural operation much less than human-altered operation. Three example systems of these regimes studied were located in western Maryland in temperate, terrestrial ecosystems of the eastern USA. The results, relations and models presented here are specific to this environmental setting, but aspects are ostensibly general enough to have potential for adaptation to many other contexts as well.

Within these differing ecosystems attention focused on soils. From prior studies, soils seemed to provide a clear and consistent indication of qualitative differences between regimes - human actions tend to degrade, consume or decrease quantity and quality of soils while natural actions tend to enhance, produce or increase them. (A few other general ecosystem properties may show similar distinct trends and thus also show qualitative regime differences, e.g., biodiversity, uniquely adapted communities and unique habitats.) For example, in terms of general overall trends, conventional, intensive agriculture tends to consume and decrease topsoil and soil organic matter (Matson 1997), while natural forests tend to produce and increase topsoil and organic matter (Baisden and Amundson 2003). (For an exception to this represented by some organic farming practices, see OFRF 2005.) This generalized knowledge aided in forming the general hypotheses that 1) soils reflect the long term, overall, net environmental effect of the different regimes, and 2) knowledge of the causes and effects of differences in soils may enable solution of the systemic human-environment problem. In other words, the approach was to seek paths and processes by which human systems might be steered or directed so as to achieve the same “bounty of the commons” of forests, starting with reversal of the general tendency to degrade soils. That this may be possible amounts to an assumption that humans need not live and operate in conflict, win-lose and zero sum relation to our environment. This is the assumption that a win-win synergy relation is possible and that its possibility provides our best odds for reversing our current trajectory.

Details of the specific study of differences in soil properties under human versus natural regimes are presented next. Then after reporting the results of comparisons of storage and vertical structure in soil carbon (C), nitrogen (N) and organic matter (OM), we will link these specific results back to the general hypotheses, inferences and proposed avenues forward toward general solution of the root human-environment problem.

Research Area and Approach

The objective was to examine and compare the total mass and vertical structure of C, N and OM in soils in human-dominated versus more natural forested ecosystems. Jobbagy and Jackson (2001) provided inspiration for this study by showing a global trend in soils of concentration of important and limiting nutrients (e.g., N, P, C, Ca) in the surface 20 cm. They attributed this “topsoil concentration factor” to “the imprint of plants”, citing the action of plants to draw nutrients up from deeper levels and deposit them on the surface in the form of litter.

The comparative ecosystem study involved fieldwork and lab analyses of soils. The study area was within the Fifteenmile Creek watershed (FCW) – an area where fellow researchers have done extensive work (Townsend et al. 2004, Sawma 2003) thus providing some starting basis of knowledge. Most of the study sites are within Green Ridge State Forest (GRSF), a 35,000-acre forest managed by the state of Maryland for multiple purposes, uses and values spanning conservation, recreation, hunting and timber production.

The research goal and sampling design was partly exploratory – to collect solid but basic data to enable preliminary analysis, and development and refinement of hypotheses, more than statistically sufficient data to test fully-defined and specific hypotheses. As such this was a pilot project designed to quantify and constrain ranges for C, N, and OM storage and vertical structure, to quantify variability in these measures and to steer future projects toward the most important variables, hypotheses and ways of testing them.

Based on Latty et al. (2004) the hypothesis was tested that total storage of C would be greater for old forest (OF) relative to younger, middle-aged forest (MF) and agricultural land (AG). Total storage of N in agricultural lands was expected to exceed the two forest types due to accumulation of N added via fertilizer and cultivated legumes. Based on Jobbagy and Jackson (2000) the hypothesis was tested that vertical structure – topsoil concentration in their terms - of C and N would differ in that C would be more concentrated in topsoil for old forest, whereas N would be more concentrated in topsoil for agricultural lands.

The nine sites and their land use histories are described in Table 2.1. Sites were chosen to keep soil type and bedrock geology constant as much as possible. This was done to enhance the ability to detect differences between the organizational or operating regimes and by minimizing natural variation in soils that might swamp out any signal of

Table 2.1. Description of the nine sites, 18 soil cores, three land use types, land use histories and soil depths.

Site Name	Site and Core	Site Type Label	Site Type	Ownership and Land Use	Dominant Species	Approximate Time in Land Use Type (years)	Soil Depth (cm)
						Based on land use history	
Billmeyer field	BA-01	AG	Agriculture	State-owned wildlife feed area	clover and grass	60-100	87
Billmeyer field	BA-02	AG	Agriculture	State-owned wildlife feed area	clover and grass	60-100	83
Cat Point Rd	CP-01	AG	Agriculture	State forest, wildlife feed area	clover and grass	60-100	53
Cat Point Rd	CP-02	AG	Agriculture	State forest, wildlife feed area	clover and grass	60-100	70
David Trail Farm	DTF-01	AG	Agriculture	private, commercial farm, hay	Big Blue Stem grass	75-100	90
David Trail Farm	DTF-02	AG	Agriculture	private, commercial farm, hay	Big Blue Stem grass	75-100	105
						Based on oldest trees	
Site 1	1-01	MF	Middle Aged Forest	State forest, logging	Chestnut oak	80-120	92
Site 1	1-02	MF	Middle Aged Forest	State forest, logging	Chestnut oak	80-120	77
Site 10	10-01	MF	Middle Aged Forest	State forest, logging	White oak	180	95
Site 10	10-02	MF	Middle Aged Forest	State forest, logging	White oak	180	98
Site RG3	RG3-01	MF	Middle Aged Forest	State forest, logging	White oak	80-120	102
Site RG3	RG3-02	MF	Middle Aged Forest	State forest, logging	White oak	80-120	90
Deep Run	D-01	OF	Old Forest	State forest, wild land, old growth	Chestnut oak	300	52
Deep Run	D-02	OF	Old Forest	State forest, wild land, old growth	Chestnut oak	300	104
Kenan Ridge	K-01	OF	Old Forest	State forest, old growth area	Pitch pine	250	49
Kenan Ridge	K-02	OF	Old Forest	State forest, old growth area	Chestnut oak	220	50
Town Hill	T-01	OF	Old Forest	State forest, logging	Chestnut oak	150	104
Town Hill	T-02	OF	Old Forest	State forest, logging	Chestnut oak	150	82

such differences. The soils for all nine sites were Calvin shaly silt loam. The Allegany County soil survey (Stone and Matthews 1977) provided soil types, locations and characteristics. Calvin soils comprise roughly 5% of Allegany County, Maryland, but are more common in the eastern part of the county. Roughly 10-20% percent of FCW is Calvin soil.

Information on sites designated as old growth forest was obtained from Maryland Department of Natural Resources (DNR). Roughly 200 acres of the 35,000 acres of GRSF are designated and protected as old growth (Harry Kahler, personal communication). Two of the old growth sites sampled were approved as officially designated old growth. The third (Town Hill) was a candidate site for old growth that was not chosen but does have older trees and other characteristics of old growth forest. Maryland DNR’s criteria for identification of old growth differ with tree species. Thus while the two predominantly oak old growth stands had trees at least 200 years old, the one predominantly pine old growth stand only had to be 100 years old to achieve old growth designation.

Two of the agricultural sites (Cat Point Rd and Billmeyer Wildlife Management Area) are state-owned and have been managed in recent years to provide food for wildlife (Francis Zumbrun, personal communication). These lands were purchased as farmland by the state in the 1970’s and are known to have been in agriculture for decades prior to acquisition. Aerial photos at the GRSF headquarters showed that both the state owned sites were cleared in 1938. Thus the sites have been cultivated for at least 60 years. The third agricultural site was the farm of David Trail. Information about this farm and its Calvin soils was provided by local NRCS staff (Ben Cooper, personal communication).

The Trail Farm has been in active production since about 1850, and was cleared and cultivated one parcel at a time (David Trail, personal communication). The field sampled has been in agricultural use since about 1900 and in intensive hay production with Big Blue Stem grass since about 1980. This farm is just outside the FCW watershed.

While all of the sites share Calvin soils and are of similar upland elevations (i.e., no bottomland or floodplain areas were included), there are some differences that could not be avoided. Two of the old growth sites (Deep Run and Kenan Ridge) were on steeper slopes than any of the other sites. Kenan Ridge and also the Cat Point Rd agricultural site were on south facing slopes and were thus hotter and drier than the others. Kenan Ridge was the only predominantly pine/evergreen site. Other forest sites were oak/hardwood/deciduous. These issues were considered during data analysis and interpretation of the results.

Field and Lab Methods

The soil sampling scheme was designed to characterize total storage and vertical structure of C, N and OM while also minimizing disturbance to sites. Thus rather than digging large soil pits, an auger was used to take soil cores. Two cores per site were located to avoid tree root and rocks using a metal soil probe. Thus samples may represent a maximum or upper range of soil depth and total C and N storage for these areas. To minimize the number of cores soil samples were alternated with bulk density samples in the same vertical profile. Surface litter was first removed and then a sample taken of the surface soil O horizon beneath a 10x10 cm plastic template. Attempts were made to exclude leaf, root, twig, bark and other litter from these samples as possible, but some litter was included. The bottom of the organic O horizon was estimated using color transition (changing from dark brown or black to brown or reddish brown) by eye and also texture transition (changing from non-gritty organic soil to gritty mineral soil) by touch. Bulk density was determined based on samples taken with a cylinder of known volume. For all samples the starting (top) and ending (bottom) depths from the surface were recorded. Holes were refilled after sampling using woody debris, rocks and excess soil as possible. Soil samples were stored in the field, and transported to the lab, in coolers on ice.

In the laboratory soil samples were refrigerated until processing. This delay ranged from a few days to two months. The longer delays were not planned but became necessary due to extenuating circumstances. Soils did not seem to change much during this time other than condensation of water on the plastic bags in which they were stored and several samples had small patches of fungal or mold growths. Auger sample soils were sieved through a 2mm sieve, weighed field wet and then dried to 70° C. Dry weights were recorded to calculate moisture content. A portion of each dried sample was ground to 100 mesh using a ceramic jar mill grinder with burundum capsules. Bulk density samples were first weighed wet, then dried to 70° C, then sieved for removal of rocks and litter. Weight of rocks and litter were recorded, and weights of rocks used for adjustments to bulk density calculations. A rock density of 2.68 g cm^{-3} was used for these adjustments for rock fraction by volume.

Total C and total N were determined using ground samples via a Carlo Erba CN analyzer. Estimates of replicate precision showed multiple %C and %N measures of very low C and low N soil samples to have a standard deviation of 0.01% and 0.005% respectively. The method detection limit was estimated as 0.001% C and < 0.001% N by running seven blanks as unknown samples. This gave an estimate of the background or noise levels of C and N. Organic matter was determined based on loss on ignition (LOI). Soils were dried to 70° C, weighed and burned in a furnace at 550° C for 4 to 6 hours following standard LOI methods of the Appalachian Laboratory. Ash weight was subtracted from initial weight to measure organic matter lost. Samples were also dried to 105° C and two 70° to 105° correction factors determined – the correction factor for mineral soil layers was 0.997 and for organic soil layers was 0.991.

Total C or N density for each layer was determined by multiplication of %C or %N by bulk density and fraction of C-bearing soils (Batjes 1996 and Smithwick et al. 2002), that is the fraction of each soil sample that passed through the 2mm sieve. This step produced C and N density in grams per cubic centimeter. To calculate total C and N storage for the whole soil profile, these C and N densities were multiplied by the length of each depth interval. This step produced C and N storage in grams per square centimeter, which was then converted to kg per hectare and Mg per hectare.

Not all samples had bulk density and rocks fraction measured. Bulk density and rock fraction for those layers without these measures were estimated from layers above and below by linear interpolation. Similarly, a few of the deeper bulk density samples were not analyzed for total C and N, so these measures were linearly interpolated from layers above and below.

Means of C and N for six depth intervals were calculated to compare the three site types or regimes. The depth intervals were 0-10 cm, 10-20, 20-40, 40-60, 60-80, and 80-

100 cm and beyond. For some of the analyses data for the one predominantly pine site (Kenan Ridge, K-01) was omitted, since it was very different in C and N profile properties.

Statistical analyses included linear regression to fit models relating C and N to depth. These regression models used log (base 10) transformed %C, %N, C density and N density as functions of log depth. To explore the validity and robustness of the linear log-log or power law relations, residuals from these linear models were examined. Additional methods, which have been recommended for testing for robust power law relations, have not yet been performed. Schneider (2001) recommends 1) use of reduced major axis regression (RMA), which assumes that both independent and dependent variables were measured with error, and 2) checking individual observations for extreme influence. These tests would improve the analyses.

Results

The main overall patterns observed were the power law distributions of C, N and OM with depth. Figures 2.1A and 2.1B show the power law curves fitted for %C and %N as functions of depth for each of the three land use types separately. The same linear log-log or power law relation was observed for C and N on percent basis (g C or N per g soil * 100; Figure 2.1) and density basis (g cm^{-3}; Figure 2.2). The one predominantly pine site core (core K-01) was unique and had the highest C and N concentrations of any site (Figure 2.1, labeled OF PI for Old Forest Pine).

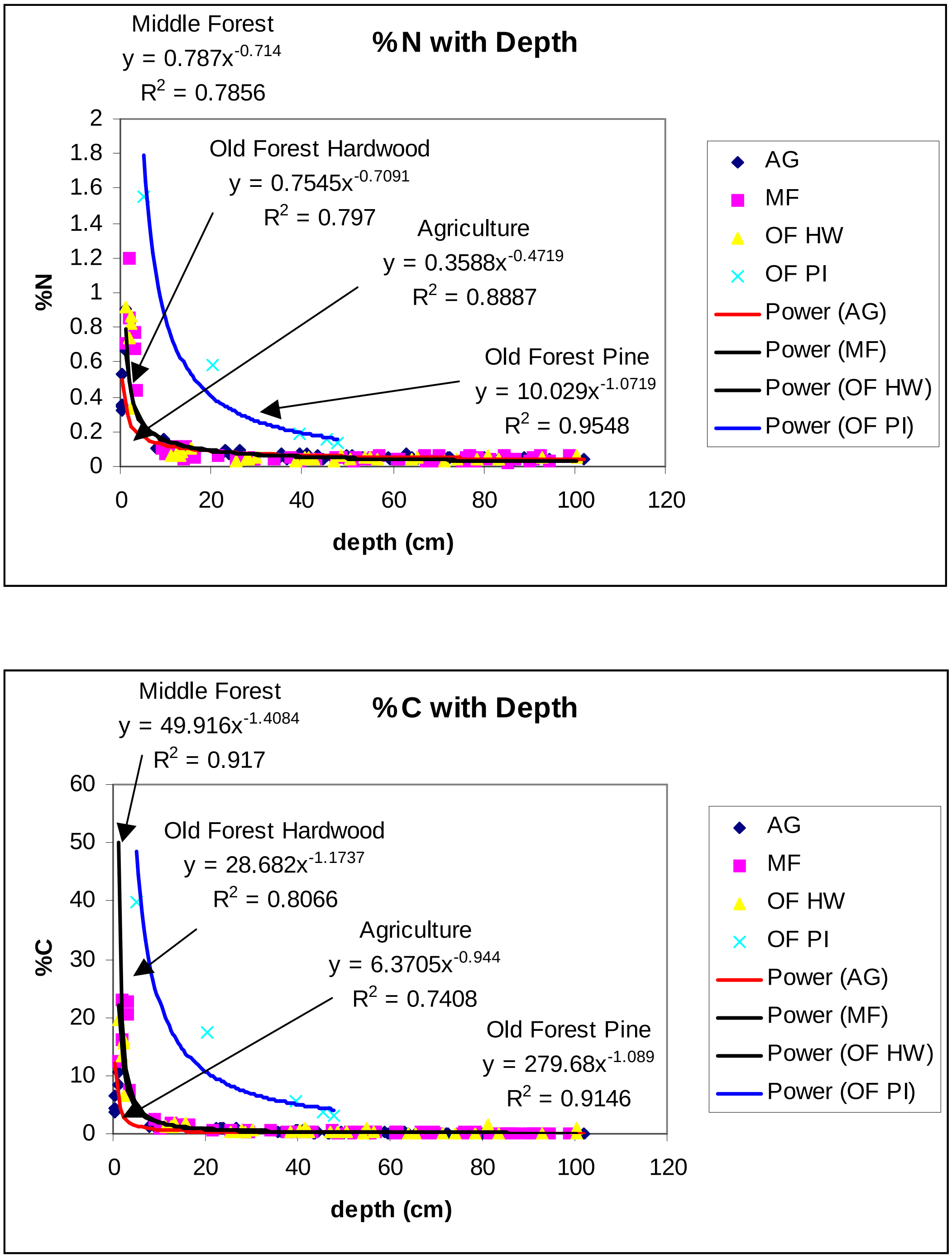


Figure 2.1A (top) and B (bottom). Power law (linear log-log) relations of %C and %N with depth. Fitted curves for Old Forest hardwood sites (OF HW) and Middle Forest (MF) overlap. OF PI is the unique Old Forest pine core within the Kenan Ridge site. Equations and R^2 values for curves are indicated.

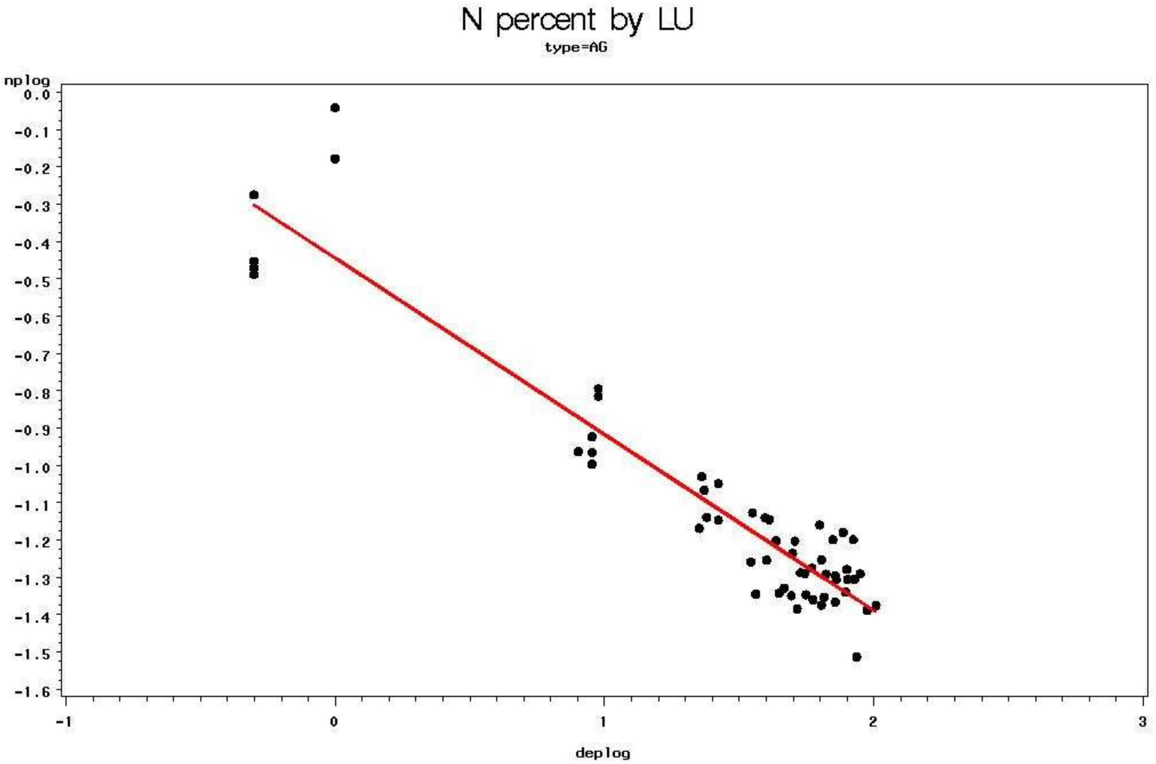
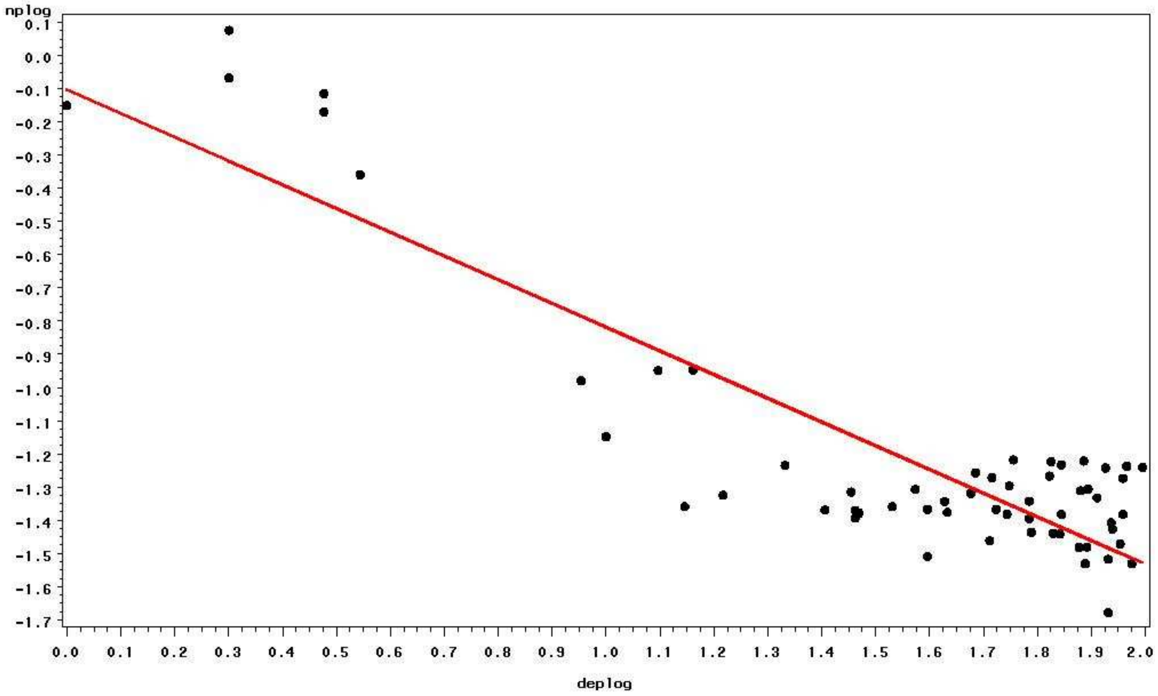


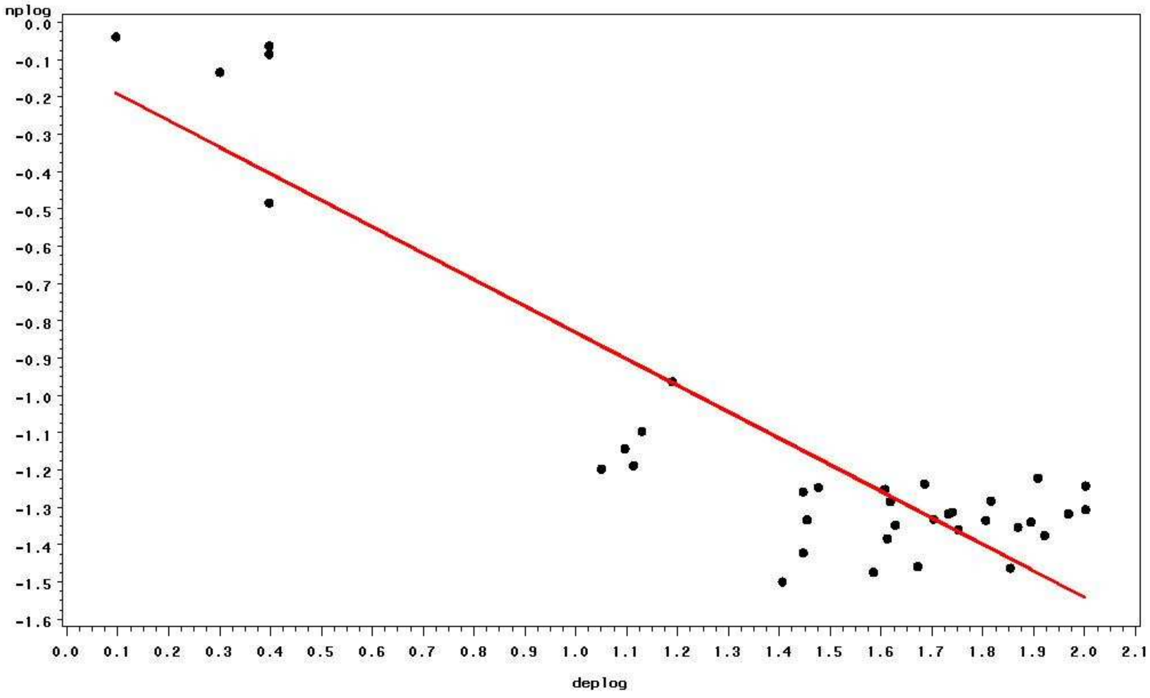
Figure 2.1C. Log-log plots of %N vs depth showing regression line and individual observations for agricultural (AG) sites.

Figures 2.1D and E (next page). Log-log plots of %N vs depth showing regression lines and individual observations for middle forest (MF) and old forest (OF) site types. Note how trend may plateau at log depth = 1.4. This relates to the apparent systematic error with depth in the residuals shown in Figure 2.5.



N percent by LU

type=MF



N percent by LU

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Figures 2.1C, D, and E show the linear log-log relationship of %N to depth for the three site types separately. The two forest site types seem to be very similar for both C and N patterns. In Figures 2.1A and B the power law curves for Old Forest (OF) and Middle Forest (MF) overlap completely, and the slopes and intercepts of the fitted lines are very similar. The agricultural sites seem quite different in vertical structure compared to the forest systems, with the difference most pronounced for C and less for N. The clearer differences in depth profiles of C can be seen in Figures 2.1 and 2.2. Another difference is apparent in the C to N ratios (Figure 2.3). Table 2.2 shows Mean %C, %N, C:N ratio by percent, C density, N density and C:N ratio by density; by site type and depth interval. Old Forest includes only the 5 hardwood plots. Figure 2.3 also shows how two cores behaved quite uniquely. Old Forest Core K-01, the only one on a pine site, had anomalously high C and N concentrations and C:N ratios. And Old Forest Core D-02 also had very high C:N ratios at depth. This core seemed to hit into a very wet and nutrient rich soil macropore. Organic matter, as determined by loss on ignition (LOI) fraction, shows similar power law trends with depth, similarity between the two forest sites, and differences between the forest and agricultural sites (Figure 2.4).

Another way in which the agricultural sites differed from the forest sites qualitatively can be seen in Figure 2.2B. For this figure both power law and exponential curves were fit to the depth profiles for C density. For the agricultural site the exponential curve for C density with depth fit better (higher R^2) than the power law model. For both forest site types, the power law model had the better curve fit. For the relation of N density to depth, all three site types fit power law curves best (Figure 2.2A).

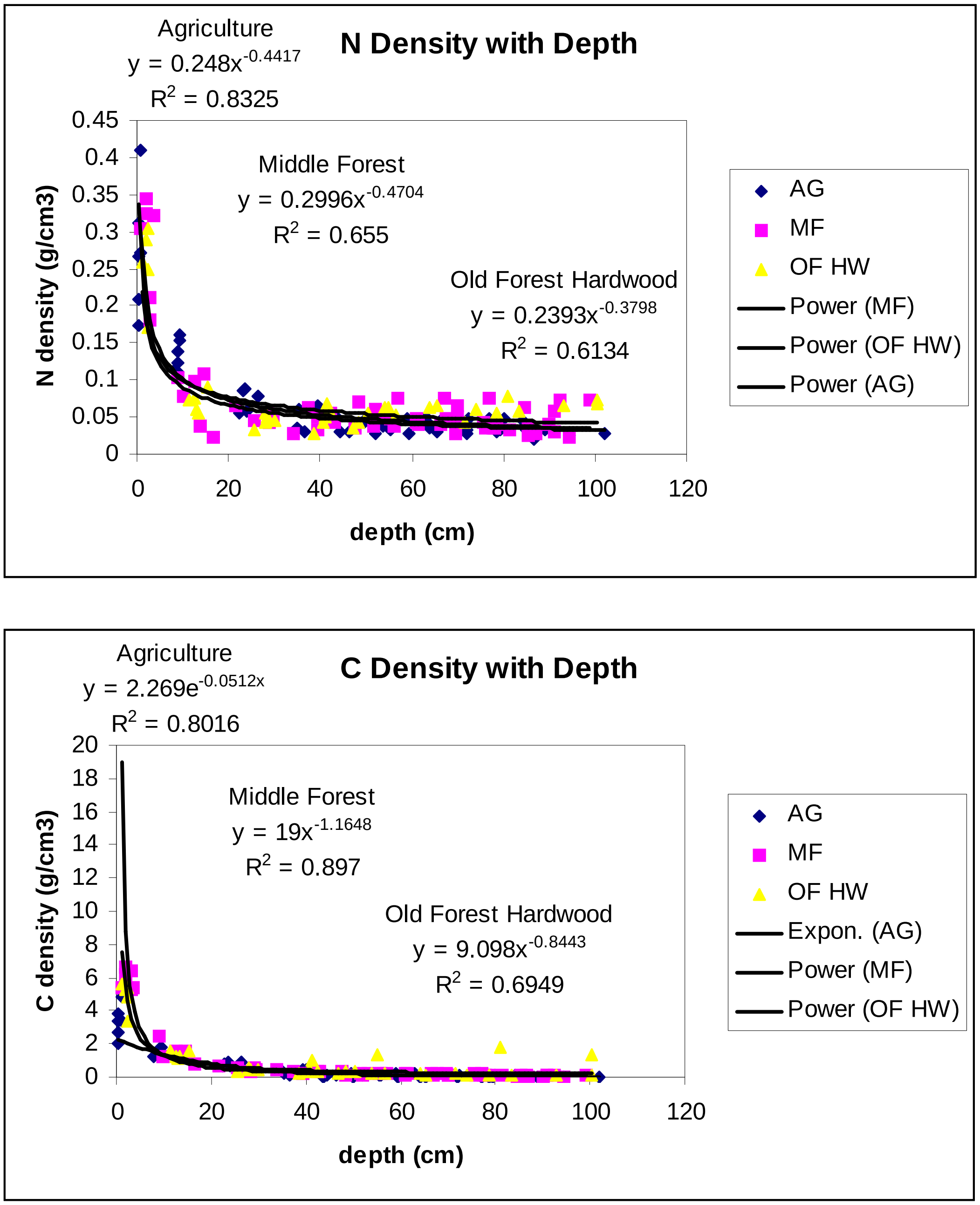


Figure 2.2A (top) and B (bottom). Power law (linear log-log) relations of N density and C density with depth. Fitted curves for Old Forest hardwood sites (OF HW) and Middle Forest (MF) overlap. The unique Old Forest pine core within the Kenan Ridge site was omitted. Equations and R^2 values for curves are indicated.

Table 2.2. Mean %C, %N, C:N ratio by percent, C density, N density and C:N ratio by density; by site type and depth interval. Old Forest includes only the 5 hardwood plots.

Site Type	Depth Interval (cm)	Number Samples	%C	%N	C:N by percent	C density (g/cm3)	N density (g/cm3)	C:N by density
AG	0-10	6	6.34	0.52	12.19	3.34	0.27	12.23
AG	10-20	6	1.49	0.13	11.88	1.58	0.13	11.91
AG	20-40	6	0.88	0.08	11.01	0.81	0.07	10.97
AG	40-60	16	0.26	0.06	4.66	0.20	0.04	4.71
AG	60-80	11	0.13	0.05	2.43	0.10	0.04	2.52
AG	80-100+	10	0.06	0.05	1.22	0.04	0.03	1.23
MF	0-10	6	17.07	0.77	22.07	5.88	0.28	20.95
MF	10-20	2	1.78	0.09	20.21	1.80	0.09	19.97
MF	20-40	10	0.94	0.06	15.90	0.83	0.06	14.69
MF	40-60	12	0.28	0.04	6.30	0.27	0.05	5.75
MF	60-80	13	0.16	0.05	3.60	0.17	0.05	3.43
MF	80-100+	16	0.09	0.04	2.08	0.09	0.04	2.05
OF	0-10	5	14.26	0.73	19.44	4.91	0.25	19.32
OF	10-20	1	1.37	0.06	21.49	1.57	0.07	21.49
OF	20-40	9	0.91	0.06	14.78	0.81	0.06	14.35
OF	40-60	9	0.36	0.05	7.80	0.38	0.05	7.80
OF	60-80	6	0.28	0.04	6.27	0.36	0.06	6.25
OF	80-100+	6	0.48	0.05	9.45	0.61	0.07	9.26

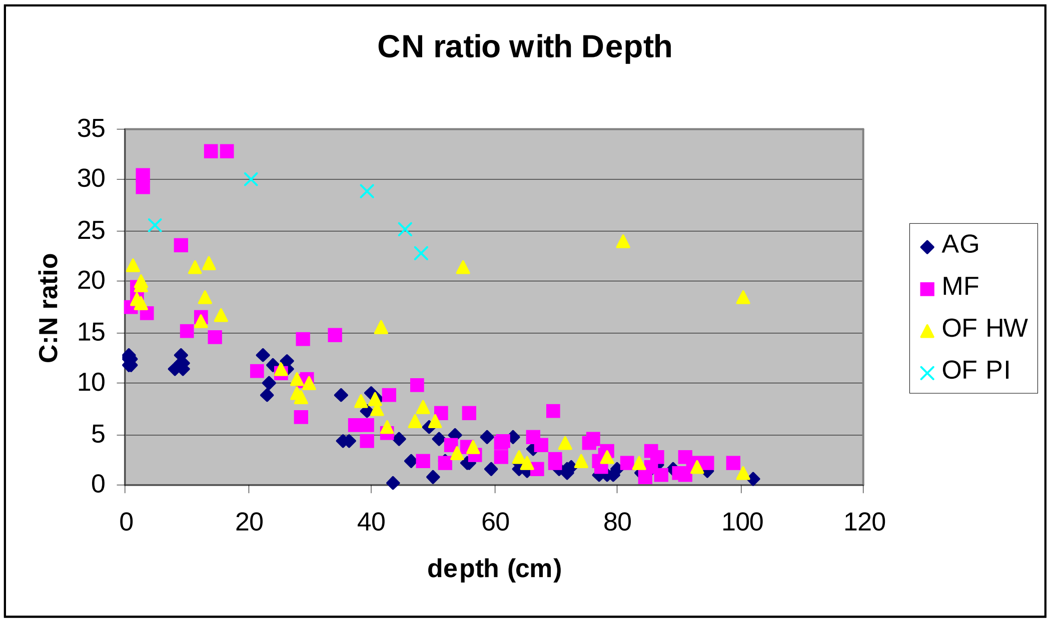
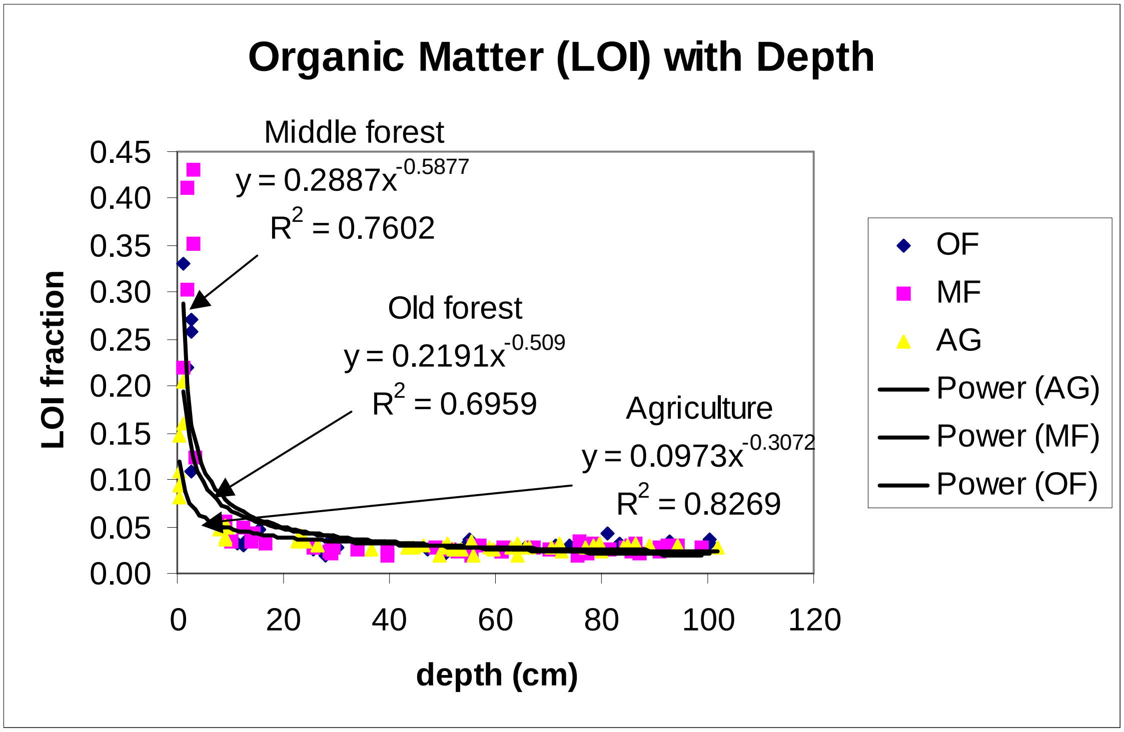


Figure 2.3. C:N ratios as function of depth. The high values in the OF HW site type came from a soil core that seemed to have hit into a very wet and nutrient rich soil macropore.



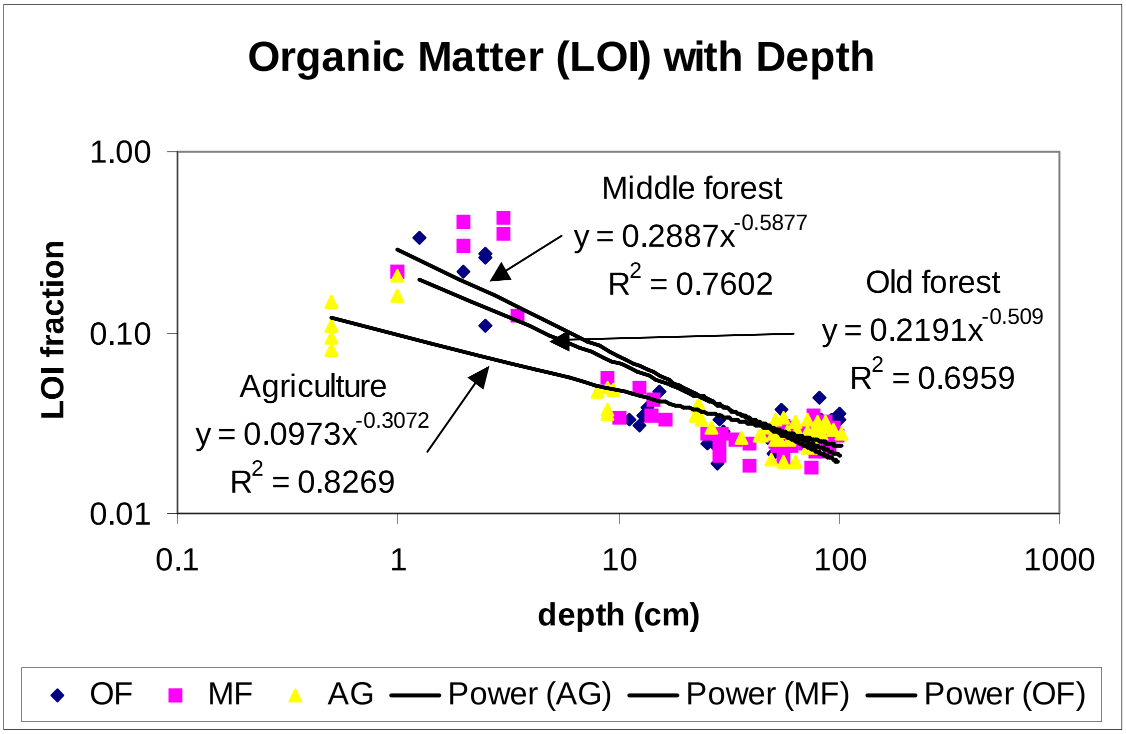


Figure 2.4. Relation of organic matter (OM) as measured by loss on ignition (LOI) with depth. Top with linear axes and bottom with log-log axes.

Total C and total N storage also showed differences between human versus natural regimes (site types) to be clear for C and much less clear or non-existent for N (Table 2.3). Mean C storage was approximately 48 Mg ha^{-1} for the Agricultural sites compared to 67 Mg ha^{-1} for Middle Forest and 58 Mg ha^{-1} for the Old Forest sites when the two anomalously high C and N cores (K-01 and D-02) were omitted or 96 Mg ha^{-1} when all cores were included. Differences in total N storage were less pronounced with soils storing about 5500, 5800 and 5000 kg ha-1 for AG, MF and OF sites, respectively (with anomalous OF sites omitted).

For an assessment of errors and variability in these measures, Table 2.4 shows mean and standard error of %C, %N, C density and N density; by site type and depth interval. The Old Forest (OF) 10-20 cm interval only had 1 sample and thus no standard error is reported. Old Forest includes only the 5 hardwood plots for these statistics.

Initial statistical tests of the power law relations between C, N and depth suggest that the relations are strong and robust. Table 2.5 shows results from linear regression using SAS software. All models and parameter estimates were highly significant except for the log %N intercepts, which thus were not different from 0. Examination of residuals from linear regression (Figure 2.5) does suggest some systematic error in the lower depths for %N in the two forest site types. This may indicate that the power law relation does not extend below about 60 cm, and below this C and N are more constant than declining in relation to depth. Residuals for linear regression of C and for C and N density measures were similar.

Table 2.3. Total C storage, Total N storage and C:N ratio by mass; by site and site type. Storage reported in both kg/ha and Mg/ha. Mean (all) for Old Forest (OF) site type includes two sites with special issues 1) an evergreen site (K-01) and 2) the core for OF site D-02 likely hit into a macropore and had unusually high values of C and N at depth. Mean OF revised omits these two cores.

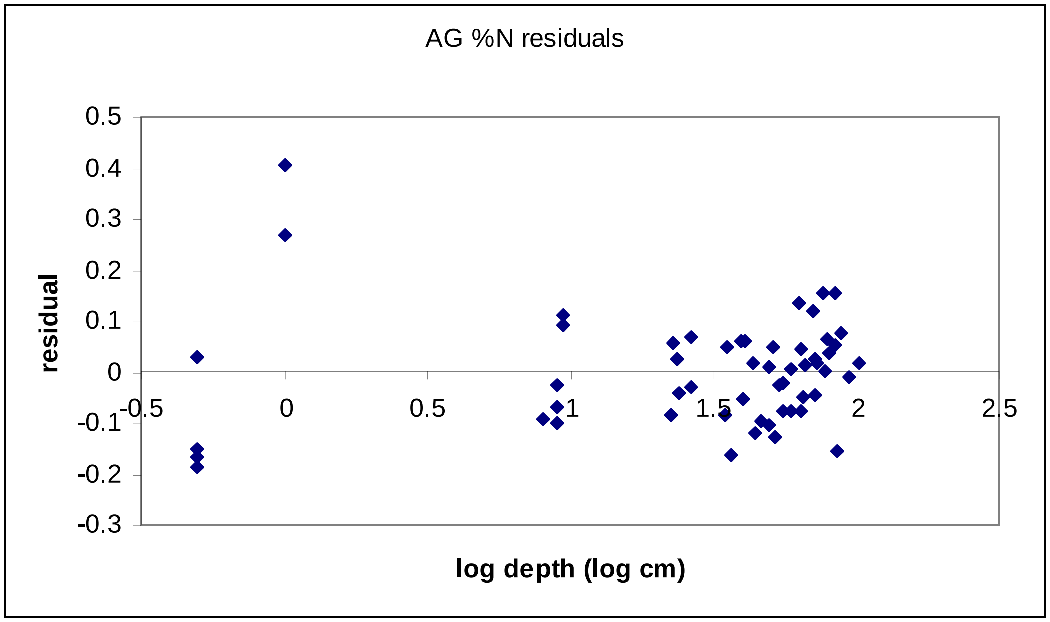
Site and Core	Site Type	Total C Storage (kg/ha)	Total N Storage (kg/ha)	Total C Storage (Mg/ha)	Total N Storage (Mg/ha)	C:N by Mass
BA-01	AG	46616	5481	46.62	5.48	8.50
BA-02	AG	50486	5489	50.49	5.49	9.20
CP-01	AG	34269	4327	34.27	4.33	7.92
CP-02	AG	55640	6043	55.64	6.04	9.21
DTF-01	AG	51918	5653	51.92	5.65	9.18
DTF-02	AG	48412	5988	48.41	5.99	8.09
Mean AG		47890	5497	47.89	5.50	8.71
1-01	MF	63981	3819	63.98	3.82	16.75
1-02	MF	77080	4342	77.08	4.34	17.75
10-01	MF	68737	6663	68.74	6.66	10.32
10-02	MF	76683	6419	76.68	6.42	11.95
RG3-01	MF	71694	8274	71.69	8.27	8.67
RG3-02	MF	43208	5076	43.21	5.08	8.51
Mean MF		66897	5765	66.90	5.77	11.60
D-01	OF	53097	3862	53.10	3.86	13.75
D-02	OF	152189	7560	152.19	7.56	20.13
K-01	OF	195298	7033	195.30	7.03	27.77
K-02	OF	68380	4470	68.38	4.47	15.30
T-01	OF	52989	6684	52.99	6.68	7.93
T-02	OF	55753	4622	55.75	4.62	12.06
Mean OF (all)		96284	5705	96.28	5.71	16.88
Mean OF revised		57555	4909	57.55	4.91	11.72

Table 2.4. Mean and standard error of %C, %N, C density and N density; by site type and depth interval. The Old Forest (OF) 10-20 cm interval only had 1 sample and those no standard error is reported. Old Forest includes only the 5 hardwood plots.

Site Type	Depth Interval (cm)	Number Samples	%C	Standard Error	%N	Standard Error	C density (g/cm3)	Standard Error	N density (g/cm3)	Standard Error
AG	0-10	6	6.34	1.10	0.52	0.095	3.34	0.39	0.27	0.034
AG	10-20	6	1.49	0.11	0.13	0.010	1.58	0.10	0.13	0.009
AG	20-40	6	0.88	0.03	0.08	0.004	0.81	0.04	0.07	0.006
AG	40-60	16	0.26	0.05	0.06	0.003	0.20	0.04	0.04	0.003
AG	60-80	11	0.13	0.03	0.05	0.003	0.10	0.02	0.04	0.003
AG	80-100+	10	0.06	0.01	0.05	0.003	0.04	0.00	0.03	0.003
MF	0-10	6	17.07	2.55	0.77	0.102	5.88	0.25	0.28	0.028
MF	10-20	2	1.78	0.70	0.09	0.017	1.80	0.62	0.09	0.012
MF	20-40	10	0.94	0.19	0.06	0.009	0.83	0.15	0.06	0.009
MF	40-60	12	0.28	0.04	0.04	0.002	0.27	0.03	0.05	0.004
MF	60-80	13	0.16	0.02	0.05	0.003	0.17	0.01	0.05	0.004
MF	80-100+	16	0.09	0.01	0.04	0.003	0.09	0.01	0.04	0.005
OF	0-10	5	14.26	2.18	0.73	0.105	4.91	0.39	0.25	0.023
OF	10-20	1	1.37	NA	0.06	NA	1.57	NA	0.07	NA
OF	20-40	9	0.91	0.20	0.06	0.008	0.81	0.15	0.06	0.006
OF	40-60	9	0.36	0.07	0.05	0.003	0.38	0.08	0.05	0.004
OF	60-80	6	0.28	0.15	0.04	0.002	0.36	0.20	0.06	0.003
OF	80-100+	6	0.48	0.25	0.05	0.003	0.61	0.32	0.07	0.003

Table 5. Results from linear regression of log transformed %C, %N, C density and N density versus log transformed depth. All models and parameter estimates were highly significant except for the forest log %N intercepts.

Variable vs log depth	Site Type	Total Degrees Freedom	F value	Model Prob > F	Model R-square	Slope	Slope Prob > t	Intercept	Intercept Prob > t
log %C	AG	54	151.47	< 0.0001	0.74	-0.94	< 0.0001	0.80	< 0.0001
	MF	58	629.68	< 0.0001	0.92	-1.41	< 0.0001	1.70	< 0.0001
	OF	35	141.79	< 0.0001	0.80	-1.17	< 0.0001	1.45	< 0.0001
log %N	AG	54	423.25	< 0.0001	0.89	-0.47	< 0.0001	-0.45	< 0.0001
	MF	58	208.89	< 0.0001	0.78	-0.71	< 0.0001	-0.10	**0.2007**
	OF	35	133.46	< 0.0001	0.79	-0.71	< 0.0001	-0.12	**0.2012**
log C density (g/cm3)	AG	54	110.41	< 0.0001	0.67	-0.91	< 0.0001	0.64	< 0.0001
	MF	58	496.37	< 0.0001	0.90	-1.16	< 0.0001	1.28	< 0.0001
	OF	35	77.44	< 0.0001	0.69	-0.84	< 0.0001	0.96	< 0.0001
log N density (g/cm3)	AG	54	263.37	< 0.0001	0.83	-0.44	< 0.0001	-0.61	< 0.0001
	MF	58	108.22	< 0.0001	0.65	-0.47	< 0.0001	-0.52	< 0.0001
	OF	35	53.94	< 0.0001	0.60	-0.38	< 0.0001	-0.62	< 0.0001



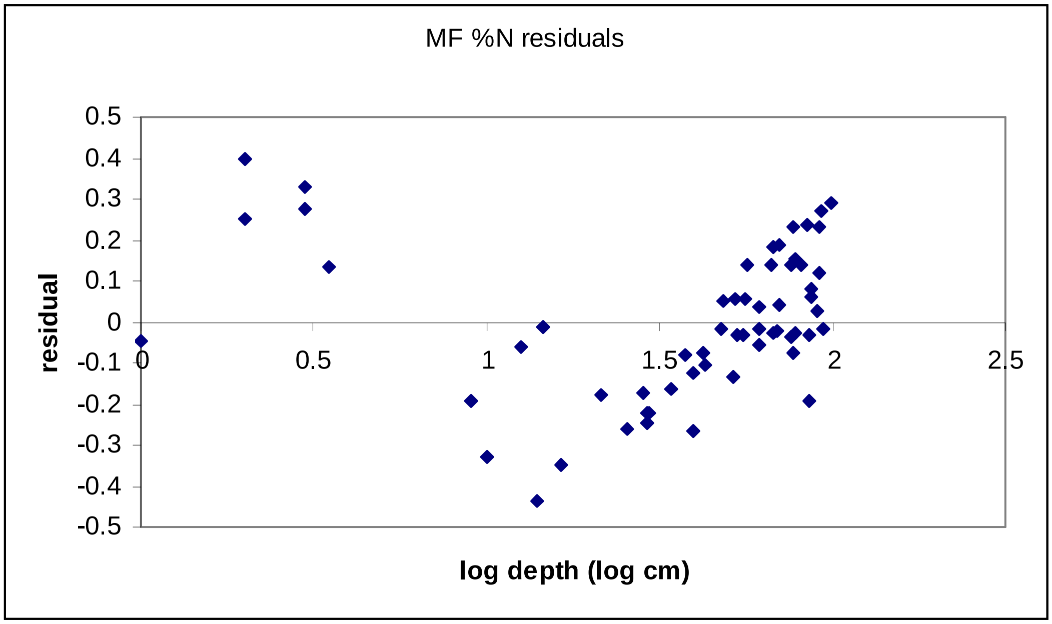


Figure 2.5. Three plots (one on the next page) of residuals from regression of log %N versus log depth. Note the potentially systematic error (linear increase in relative error with depth) for forest sites (OF, MF) at depth.

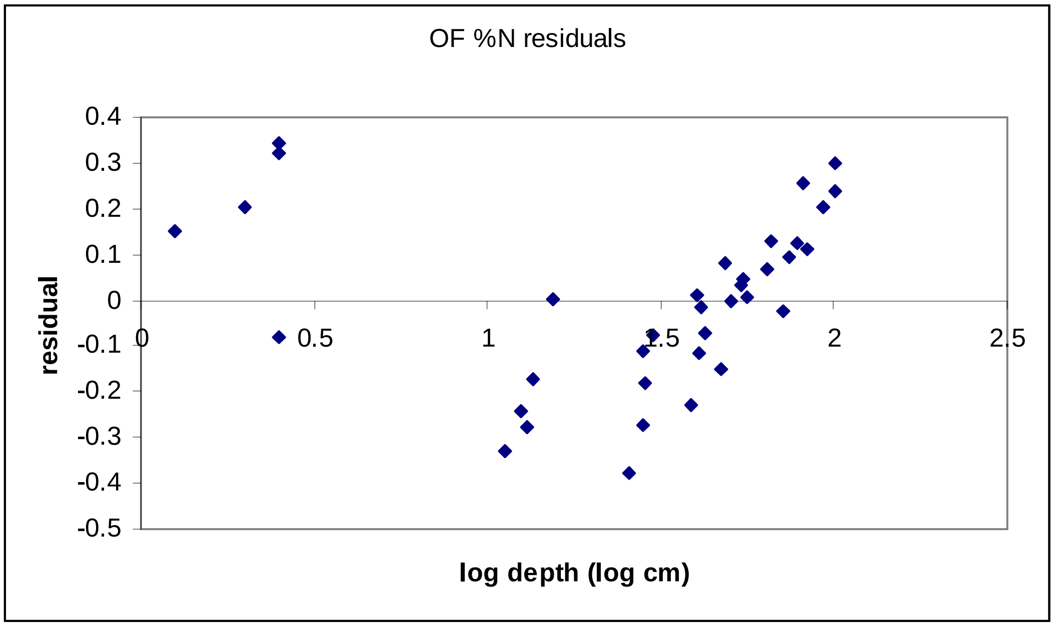


Figure 2.5, continued.

Discussion and Conclusions

The total C and total N storage values observed in these soils are comparable to those reported by others. Latty et al. (2004) reported total C storage of 67 versus 50 Mg ha^{-1} and total N storage of 3.3 versus 3.0 Mg ha^{-1} for old growth versus logged and burned forests, respectively, in the northeastern USA. These estimates are very similar to observations for total C, and significantly less estimates of total N storage (ranging from 5 to 5.8 Mg ha^{-1}), in the present study. Jenkins (2002) reported soil organic carbon storage of 9 to 20 kg m^{-2} in forests in nearby West Virginia. In the top 30 cm of soil only, Richter et al. (2000) observed total C storage ranging from 19 Mg ha^{-1} for old field pine to 33 Mg ha^{-1} for hardwood forest, and total N storage ranging from 1000 kg ha^{-1} for old field pine to 2300 kg ha^{-1} for agricultural hay fields in South Carolina in the southeastern USA. These stocks of total C and N are both less than found for Western Maryland when summing up total storage to 100 cm depth. Smithwick et al. (2002) reported total C storage ranging from 27 to 472 Mg ha^{-1} for forests in Oregon in the northwest USA. These upper estimates for Pacific coastal rainforest are 5 to 8 times greater than the C storage estimated for temperate Mid-Atlantic forests and agriculture.

Relative to the original hypotheses of the relations of C, N and OM storage and vertical structure by land use, some aspects were supported and others not. Total C storage did trend as OF > MF > AG when all OF sites were included, but changed to MF > OF > AG when the two sites (K-01 with pine and D-02 with an apparent wet macropore) with very high C and N were omitted (Table 4). In terms of topsoil concentration of C, OF and MF forests were very similar, but both were greater than AG as hypothesized (Table 3). Total N storage trended as MF > OF > AG when all sites were included and MF > AG > OF when the OF pine and macropore cores were omitted (Table 4). Neither of these supported the hypothesis that AG sites would have greater N storage due to added N fertilizer and cultivation of legumes. Topsoil concentration of N was very similar for AG, MF and OF site types. AG sites did appear to have a slight shift downward such that both 0-10 and 10-20 cm layers had significant N by percent and density, whereas for the forest sites the drop off from N in the 0-10 versus 10-20 layers much more rapid. In this sense topsoil concentration was related as OF = MF > AG, again in opposition to predictions made assuming differential N additions of agriculture.

One factor that arose during the research that explains some of the differences in predicted versus observed patters is that the Old Forest (OF) sites did not seem representative of old growth as natural, mature forest. Instead, two of the OF sites (Kenan Ridge and Deep Run) were remote, steep and rocky sites that were likely passed over for logging and left as remnants partly due to poor site quality and difficulty of access. Steeper slopes and thinner, rockier soils likely affected the estimates of soil C and N and may have contributed to lower than expected C and N when the anomalous cores were omitted.

During fieldwork observations indicated that the three agricultural sites had little or no distinct organic layer at the surface. In order to make an estimate of the surface layer the top 1-2 cm of soil was scraped and sampled, but this soil was largely mineral soil mixed with vegetation litter. There was no black and humic soil layer in the agricultural sites, and this is reflected in the much shallower depths of the surface layers (data not reported) and the C and N densities reported (Table 3).

Many other studies have shown similar patterns of the distributions of C and N with depth. Jobbagy and Jackson (2001) show a general global pattern of topsoil concentration (greater nutrient concentration in the top 20 cm of soil than would be expected with a uniform depth distribution) for many limiting nutrients include C and N. Jobbagy and Jackson (2000) have also modeled the structure of C with depth and found that a log-log function of C with depth fit better than any other model tested. Jenkins (2003) shows the same steep drop off of C and N in forests in nearby West Virginia. Arrouays and Pelissier (1994), however, found that an exponential function best explained depth profiles of C in temperate forests in France. The consistency of this pattern enabled Arrouays and Pelissier (1994) to reduce the number of soil samples needed for estimation of total C in soils from ten to three.

Ecosystem models often employ a structure with multiple pools of soils C and N that turnover at widely different rates. Baisden and Amundson (2003) employ three pools of soil C and N in their analytical model – an “active” pool turning over on an annual time scale, a “slow” pool turning over on a decadal time scale, and a “passive” pool turning over on a millennial time scale. They suggest this model structure provides sufficient detail to depict key patterns of soil accumulation over time periods up to 10-15,000 years. Their model fits a chronosequence of soil development very well, and shows that the slowest changing, most recalcitrant soil C and N pools can continue to develop and aggrade over 10,000 years. They explain the differing pools and turnover rates relative to different degrees of available energy and carbon (from labile to recalcitrant) as well as the energy required to decompose these differing substrates. However, they do not seem to offer any explanation for the origination or continued regeneration of this 3-pool structure that they say is consistent across most ecosystems.

No studies found so far explain how or why this characteristic structure of differing turnover rates of soil C and N pools exists, nor have any linked the observed difference in turnover with depth profiles. The author is also not aware of any theories on whether this widely observed vertical structure of C and N storage 1) might confer benefits or be of adaptive or survival value for individual species or organisms, or communities considered as integral wholes, or 2) might provide feedbacks between biotic and abiotic subsystems within ecosystems.

Power law distributions can sometimes be generated by the interplay of two antagonistic forces operating at exponential rates of the same order of magnitude, and the “critical scale” is defined as the space or time range over which the two antagonistic forces are of the same order of magnitude (Schneider 2001). One example of two such antagonistic forces interacting to produce power law spatial patterns is birth versus mortality of organisms (Schneider 2001). If the pattern of power law scaling of C, N and OM with depth could be connected to such interplay of two opposing exponential rates, it could provide a general, ecosystemic explanation for the structures of soil C and N. The two major rates involved in forest ecosystem carbon flux are carbon fixation (input) via plant photosynthesis and carbon respiration (output) via plant, microbial and animal respiration. These two rates and annual fluxes are often very closely matched such that net ecosystem production (NEP) is often a relatively small positive number and can become negative during times of disturbance (Aber 1999). And these two rates are likely of the same order of magnitude over very long time scales such as the 10,000-year period over which soils are often developed.

Figure 2.2B shows that the relation of C density with depth is qualitatively different for agricultural versus forest site types in that an exponential model fits better for agriculture than does the power law model. This difference is related to the greater storage of C and N in the surface organic layers of forests and the near total depletion of this organic layer following extended agricultural production. Additional tests of whether the power law relation fits better than a log-normal curve would improve the results (R. Ulanowicz personal communication). This distinction combined with knowledge that agriculture usually depletes soil C and organic matter (Matson et al. 1997) provides a potential link between power law depth distribution of soil structure and net environmental trend of accumulation (forests) versus loss (agriculture) of soils as a form of “natural capital”. To the degree that soil and soil C, N and organic matter are widely known to provide benefits of water holding capacity, nutrient reserves and enhanced primary productivity this provides a further link between soil structure, net environmental trend of soils and community productivity and resilience.

This combination of ideas suggests the hypothesis that the natural regime’s power law soil structure arises from a matching of the magnitude of two opposing forces while the human regime has altered or shifted the interplay favoring one of the antagonistic forces over another. If the explanation of two antagonistic exponential rates is valid, and if these two rates tending in opposite directions must be of the same order of magnitude, then it is possible to imagine that changing the relative proportions of the two rates could change 1) the interaction or interplay, 2) the power law pattern as it is shown in the memory of the soils, and 3) the net trend or “bottom line” in terms of long term accumulation or loss of soils and soil C, N and OM.

The general and predominant goal of conventional agriculture is production as provided by harvest. For commercial farms to survive economically, harvest must be produced in such way to provide financial profit after sale and accounting for financial costs. In this regime or system organization, N in the form of fertilizer is often added to stimulate production of N-limited crop plants. Both C and N are removed from agroecosystems with the harvest of crops or livestock. In this sketch of the agricultural process are evident both the increase in C removal by harvest and the alteration of the C:N ratio by addition of N and removal of C. In terms of the two hypothetical input and output rates of carbon, the near balance seen in forests has been shifted such that removal is likely much greater than additions of C. This potential shift away from a match in order of magnitude of antagonistic rates of C input and removal, if it could be better quantified and corroborated, could explain both the differences in soil C depth profile and net environmental trend of accumulation versus loss of soils under natural versus human-dominated ecosystem regimes.

Several other options exist for antagonistic rates or forces that might interact to produce the power law pattern of soil C and N with depth. One might consider plants and autotrophic organisms as ecosystem “composers” of organic C and N and animals and heterotrophic organisms as “decomposers” operating in opposite fashion to convert organic C and N to inorganic forms. These two subsystems of terrestrial ecosystems, as located above- and belowground, are increasingly seen, studied and depicted as strongly coupled and interdependent (Wardle 2002, Wardle et al. 2004). This approach fits with the work of Likens et al. (1978) who attributed the homeostatic and nutrient retention capacities of forested watersheds with “functional balance” and “intrasystem cycling”. These two properties were disrupted by their experiments to clear-cut entire watersheds, thus removing the nutrient and water uptake and carbon fixing actions of autotrophic functional component while leaving the heterotrophic subsystem relatively undisturbed.

Another possible antagonistic, dialectical or complementary distinction might be made between increases in production versus increases in “productive capacity” such as various internal structure forms (e.g., woody supporting biomass) and external alterations of the environment (e.g., accumulation of soil organic matter). Similarly, a dynamic tension may exist between short term versus long-term evolutionary gains or community improvements. Using this distinction it seems that terrestrial forest operation (in temperate ecosystems, over the past roughly 10,000 years) is biased toward long term gains resulting in storage and net accumulation of soils, while human agricultural operation has been biased toward short term consumption resulting in net loss of soils. Yet another set of antagonistic forces exists in the action of plant uptake and evapotranspiration to draw water and nutrients upward countered by the gravitational force that operates to draw water and nutrients downward.

Fath et al. (2001) have reported an analogous apparent antagonism or dialectic in their integration of ten ecological goal functions or system orientors. They suggest that analysis of ecosystem networks of material and energy fluxes and storages show a general tendency toward maximum storage and cycling while at the same time tending to maximize dissipation and flux through the system. This apparent contradiction is resolved by considering a third tendency of natural living communities to maximize residence times of energy and nutrients. This consideration of increasing residence time makes it possible for ecosystems to increase rates of both storage (linked to cycling) and flux (linked to dissipation), as long as the rate of storage increases somewhat faster than the rate of dissipation increases. Thus by this analysis two opposing tendencies – storage and dissipation – become synergistic rather than antagonistic as long as residence time increases. Another landmark paper by Fath and Patten (1998) shows how the emergence of synergism or positive, mutualistic relations between participants in ecological networks is to be expected. This counter-intuitive property that seems to go against the grain of conventional Darwinian and competition theories results from three network properties of 1) symmetry as ensured by conservation of matter and energy, 2) indirectness of relations and a dominance of indirect over direct interactions, and 3) openness to inputs of matter and energy.

A possible approach to develop this line of thought further would be to consider how human-dominated agricultural systems differ in their ecological network configurations relative to natural forested ecosystems. The idea would be to search for a robust and organizational, relational, informational and/or topological way in which 1) natural systems synergize or turn apparent conflict between two potentially antagonistic forces into an advantage resulting in net ecosystem gains of nutrient and/or energy capital and 2) human systems deviate from this natural organizational/relational synergy resulting in antagonism and net ecosystem loss of nutrient and/or energy capital.

Ulanowicz (1997) has presented a perspective based on the importance of indirect mutualism and autocatalytic loops within trophic flow networks. He uses network methods and indices based on information theory and shows how observed networks are structured in ways very different from randomly connected networks and also exhibit power law distributions (Ulanowicz and Wulff 1991). Using his approach it might be possible to elucidate the organizational/relational keys to both natural synergism and human antagonism of opposing forces. A few initial steps in this direction are presented in Figure 2.6.

In the three parts of Figure 2.6, starting from an initial, basic, fully connected network with three components, one could constrain potential flows in two different ways that might be analogous to 1) an autotrophic or “composer” view of the world focused on energy and/or carbon as the primary currency, and 2) a heterotrophic or “decomposer” view of the world focused on matter and/or nitrogen as the primary currency or exchange value. Rather than develop independently, however, the idea is to explore whether these two models or representations of the world might develop interdependently, in synergy or mutually beneficial interaction. Such interdependence could be based on the fact that while composers “trade” or exchange carbon or energy, they are nitrogen limited and vice versa – decomposers focus on, produce, trade or exchange N while they are primarily limited by carbon or energy. Thus there is a complementarity in the relative exchange versus use values – composers see carbon for its exchange value and see nitrogen for its use value, and decomposers do the reverse.

Ulanowicz (1997) provides detailed description of the steps needed to quantify and analyze ecosystem flow networks using information theory. His work quantifies the average mutual information (AMI) as related to the constraints of actual network flows relative to all possible flows and identifies AMI as a central organization principle by which communities grow and develop. It should be readily possible using his techniques to quantify the composer-type information in the network in Figure 2.6B, the decomposer-type information in the network in Figure 2.6C, and the second order, synergistic or relational information between these two first order types of information. That is, to quantify the interdependent or mutual information represented by the two complementarity or differences between the two alternative views of the world. This is one option for future efforts in this research. Once completed, this analysis could be applied to examine how the alterations to ecosystem flows in human-dominated and agricultural regimes differ in their informational and organizational constraints.

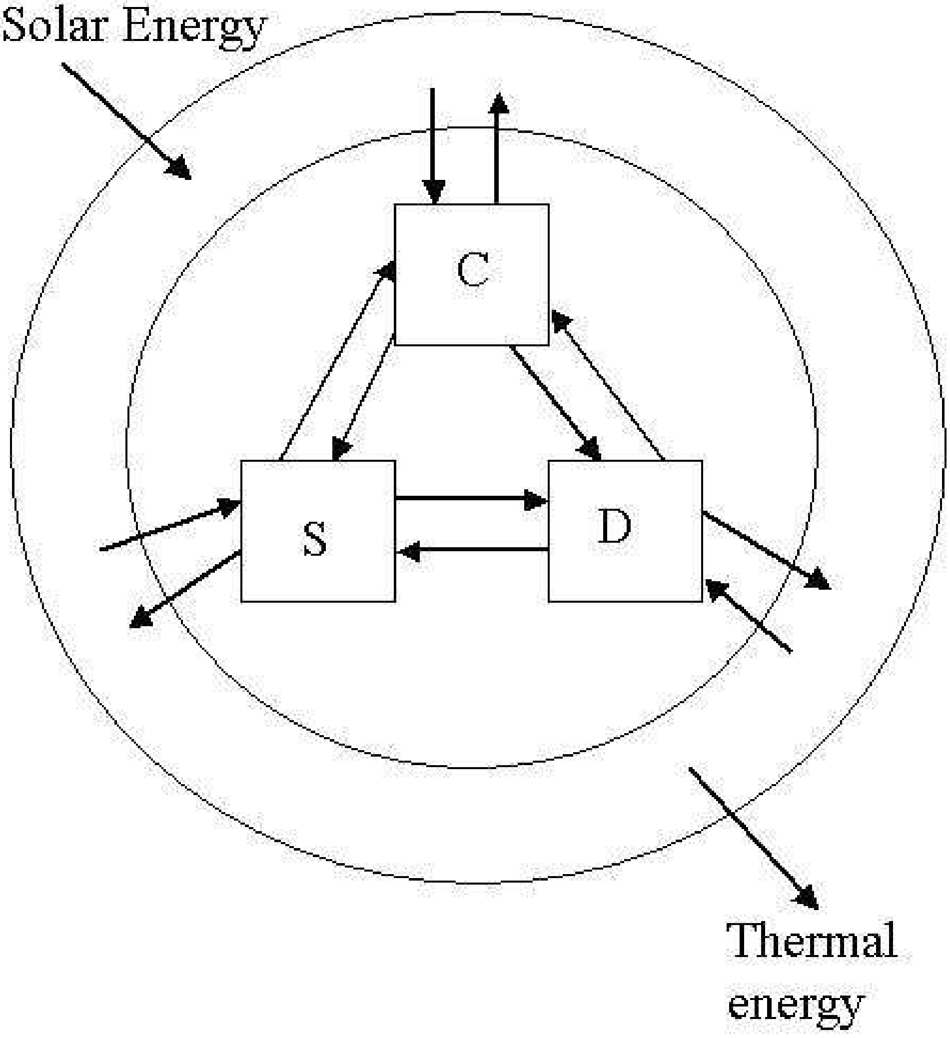


Figure 2.6A. Unconstrained, fully connected potential ecosystem network with hypothetical components or roles for autotrophic or “composer” functional types (C), heterotrophic or decomposer functional types (D) and abiotic, non-living soils (S). The inner circle represents a local, community boundary, closure or region of cycling of carbon and nitrogen and the outer circle represents a global, biosphere boundary of the atmosphere within which carbon and nitrogen cycle as gases.

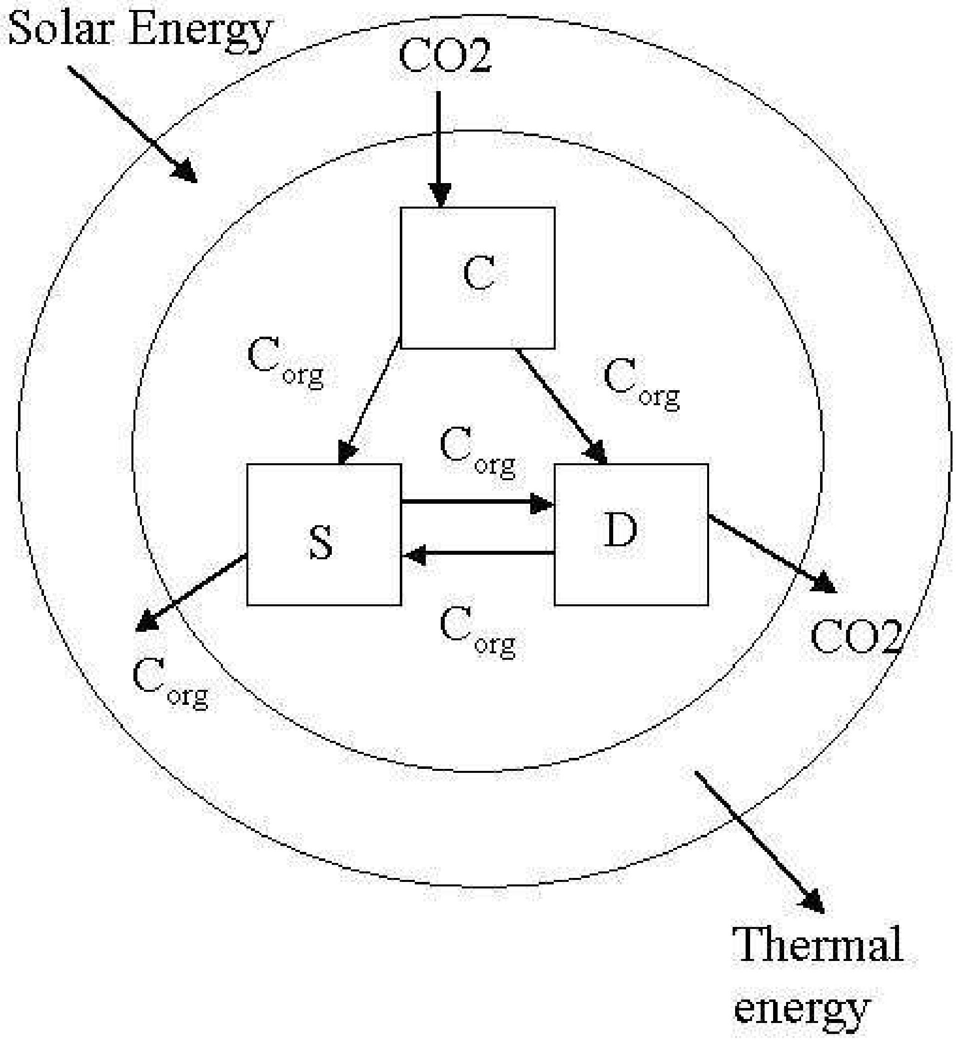


Figure 2.6B. Constrained network in which some of the potential links in the fully connected network have been removed or decreased in relative importance and weight as seen from a carbon- or energy-focused or “composer” view of the world. C_{org} denotes organic carbon. Note the single predominant loop of local carbon cycling between soils and decomposers. Also note decomposers D only obtain carbon from local, organic sources.

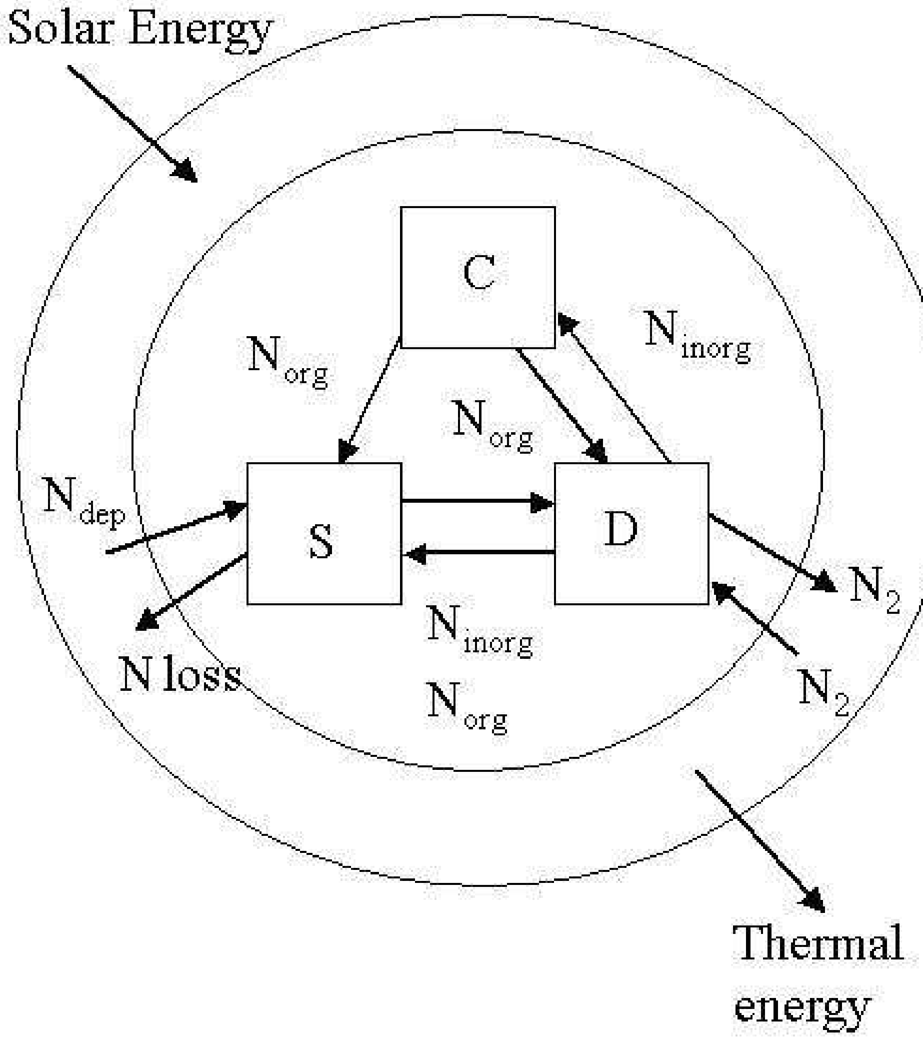


Figure 2.6C. Constrained network in which some of the potential links in the fully connected network have been removed or decreased in relative importance and weight as seen from a nitrogen- or material-focused or "decomposer" view of the world. N_{org} denotes organic nitrogen, N_{inorg} is inorganic nitrogen, N_{dep} is atmospheric nitrogen deposition; N_2 enters via symbiotic N_2 fixation and leaves via microbial denitrification. Note the two loops of local N cycling between soils and decomposers and between composers and decomposers. Also note composers only obtain nitrogen from local, inorganic sources.

Speculation, Questions and Potential Implications for Action

Perhaps more questions have been raised than answered in seeking systemic solutions to the general human problem of environmental degradation. How does the scaling of C, N and organic matter link to net ecosystem gains and a “bounty of the commons”? Is the decreasing C:N ratio with depth related to a form of energy, matter or information storage? Do deep soils and/or power law depth distributions provide a buffer against disturbance, a “nest egg” or reserve capital for recovery from disturbance? Does the difference between C-limitation of microbes and N-limitation of plants play a role? Can soil depth be a surrogate for some measure of time and/or space? Is there evolutionary or other benefit to structure in soil lability vs recalcitrance on all scales spanning long times like the 10,000 years of soil development? These questions may provide incentive for specific future studies. In general, this work inspires the sense that soils are an excellent arena in which to study fundamental qualities of life-life and life-environment relations.

By connecting the structures of soils, the net environmental tragedy or bounty under alternative regimes and the organizational, informational or relational aspects of community configurations, we may find a path by which science can aid humanity in moving beyond conflict to synergy with our global home environment. It was assumed at the beginning, and this works apparently supports the idea that ecosystems can do both, to have the best of both worlds, in almost any case of apparently antagonistic forces. Both production and productive capacity can be increased. Both energy and matter can be used, stored and traded. Both plant “composer” and microbial or animal “decomposer” organisms and populations can and must grow together. Forest ecosystems are living proof that these and other seemingly zero sum trade-offs can be resolved to the benefit of both individual life forms and whole communities. We have more work to do to understand the principles behind this synergy and even more work beyond that to embody and realize those principles in human systems, in human-human relations and in human-environment relations.

If we were to assume that the principle of synergy is close to the crux of the matter, we could explore application of this principle in several problematic human-environment problem realms. In each attempt at application we would be seeking to mimic the relations and organization inherent in forests and other natural regimes. For agriculture in the mountainous regions of the eastern USA, applied synergy would suggest that we “farm like a forest” and that we attend to both production and productive capacity, that we grow crops as well as soils. For development, applied synergy would imply that if we add people, consumers, decomposers to the land in an area, rather than remove, reduce or displace the plants, producers, “composers” there, we would add more. In the realm of economics, applied synergy suggests the need for dual currencies – one currency perhaps designed to help value long-term community needs or “use value”, and another to help value short-term community needs or “exchange value”. (see Hornborg (2001) for expert exploration of the importance of dual currencies.)

Lastly, in the realm of science, applied synergy and mimicry of the relations of the natural ecological regime suggests a “balance of models of nature” as being more important than the debate over whether there is a “balance of nature” (Milne and Milne 1960). The dominating influence of a single operational paradigm such as the current mechanistic, reductionist, objectivist science program seems to skew science away from synergy of knowledge, just as the dominating influence of production skews agriculture away from the composer-decomposer synergy that may generate soils. While optimization of a method or approach has value, an equally valued and countervailing or self-critical function appears needed as well. Otherwise, how are we to prevent against a situation in which the traditions and prevailing views are more important that the discovery of new knowledge? This extended quote by Peter Elbow (1986) highlights these issues:

> "This epistemological dilemma has shown up particularly vividly in particle physics. Physicists cannot get information about a particle alone. They can only get a package of information about the interaction of the particle and the "observer" (i.e., the equipment). They can know the velocity of a particle, but not its location, or its location but not its velocity; but they cannot know both.
>
> The dialectical pattern of thinking provides some relief from this structural difficulty inherent in knowing. Since perception and cognition are processes in which the organism "constructs" what it sees or thinks according to models already there, the organism tends to throw away or distort material that does not fit this model. The surest way to get hold of what your present frame blinds you to is to try to adopt the opposite frame, that is, to reverse your model. A person who can live with contradiction and exploit it - who can use conflicting models - can simply see and think *more*."

And one page later:

> "Searching for contradiction and affirming both sides can allow you to find both the limitations of the system in which you are working and a way to break out of it. If you find contradictions and try too quickly to get rid of them, you are only neatening up, even strengthening, the system you are in. To actually get beyond that system you need to find the deepest contradictions and, instead of trying to reconcile them, heighten them by affirming both sides. And if you can nurture the contradictions cleverly enough, you can be led to a new system with a wider frame of reference, one that includes the two elements which were felt as contradictory in the old frame of reference."

A final quote by Niels Bohr corroborates the potential importance of coupled complementary approaches to science that may someday mimic the coupled complementary worldviews interdependent in living systems. Bohr said "A Great Truth is one for which its opposite is also a Great Truth." Based on the advice implied in this definition, synergy between opposing views of the world is necessary for the generation of truly profound and valuable knowledge.

One of the original hypotheses at the start or this project was that *science itself* - and the dominant mechanistic, reductionist, objectivist, "predict and control" mindset or worldview that diffuses from science into technology, agriculture, economics, development and environmental management - *is the systemic underlying root cause of the fundamental humans-in-the-environment problem.* This explanation also seemed to explained why the problem has been so hard for us scientists to address and solve – it is hard to see yourself as the cause of a problem when you have been trained for years to remove yourself from all analyses and focus exclusively on the world objectively.

In accord with the working assumption that science was the cause of our systemic environmental problems, the working solution has been to "heal the epistemic, Cartesian cut" – to build bridges and reconnect lost integration across the boundary between knower and known, between scientist and system of study. Following this thread one may surmise that we in science are obligated to lead by example and to convert our own operations to sustainable practices first and immediately. Sustainable is used in the sense of reliance on renewable energy, recycling materials processes, both achieved simultaneously by mimicry of natural systems and their synergy of energy-matter, composer-decomposer interdependence relations. This approach suggests that unless we account for the actual biophysical, energy, materials, soils, biodiversity and other ecosystem service costs of science, we cannot know if science is producing net benefit to humanity or net detriment. This effort still seems worth doing, and the author kept notes on energy and materials use during this project to enable estimates of carbon and nitrogen uses and emissions.

But based in part on the lessons learned during this work, science no longer appears as simply the cause of the human-environment systemic problem. Instead, science may be both the cause and the solution. It is at this seemingly contradictory interface that future work will be conducted, hopefully with more synergy and less antagonism.

Chapter 3

Self-examination of Environmental Science as an Environmental Process

Know thyself. Inscription at the entrance to the Temple of Apollo at Delphi, Greece

I have not yet seen one who could perceive his faults, and inwardly accuse himself.
Confucius, from The Analects

Introduction

The current world environmental situation presents a challenge to science and scientists in at least two fundamentally different ways. On one hand, the global environmental crisis (Manuel-Navarrete et al. 2004, Leigh 2005) challenges science to help discover the knowledge and develop the technologies with which societies, communities and organizations can solve myriad environmental problems now confronting humanity. On the other hand, the all-encompassing nature of the crisis challenges science to consider whether its historic strengths and successes – where objectivity and independence have formed the philosophical basis for the analytical and experimental methods of science – are sufficient for addressing the current novel type of problem. All of humanity and science itself are clearly inside the "system boundary" drawn when large-scale environmental problems such as climate change or eutrophication of surface waters are studied. Thus the choices, values and actions of scientists affect research into the nature of the problems as well as proposals, designs, implementation and assessment of the success of solutions. These two science challenges might be considered an *objective challenge* to produce more *objective knowledge about the external world*, and a *relational challenge* to develop more, and new forms of, *knowledge of humans and science itself in relation to an external world*.

Much like mainstream economics and corporate business, most practitioners and approaches to science “externalize” environmental costs. That is, expenditures of environmental capital or natural resources are removed from consideration when assessing progress and success or gains and losses of capacity. Even within environmental science there has been very little explicit and conscious accounting of environmental costs or tracking of trends in the environmental resources required for conducting science, such as supplies of energy needed to manufacture and operate specialized equipment and computers. Instead, other measures are used for evaluation of success and progress, such as numbers of articles published, impact factors of those articles, students advised and competitive grant dollars won.

Science may become even more complex if we begin to internalize environmental costs, but the benefits may more than compensate for the added complexity. Considering options for internalizing accounting of the environmental capacity to do science, one must also decide on spatial and temporal extents or boundaries with which to define a science entity as well as the environment from which, and time frame over which, it receives its needed supplies and emits its wastes. In perhaps the most conservative approach, determination of both environmental supplies and waste absorbing capacities are local, and any such accounting must be integrated with specific details of the local environment. This conservative approach excludes the option for subsidies from afar and emissions of wastes left for others downwind and downstream.

The study reported in this paper was conducted in the context of a multi-part research project seeking to contribute to lasting solution of excess nitrogen (N) loading from land to waters and related environmental problems. The study was designed to approach the problem of excess N loading – as an example representative of many other current environmental problems - from an alternative and complementary perspective. Rather than looking “outward” to analyze those external causes of excess N loading in sectors like agriculture, transportation, industry, housing, development, etc. the goal of this study was to look “inward” at how environmental science itself is related to such problems. Before setting out the specific questions and goals of this study, more details on the context of current environmental problems are presented next.

Characterizing Human-Environment Problems

The frequency and gravity of environmental warnings coming from science seem to be increasing. The Millenium Assessment (Millenium Assessment 2005) stated that 60% of the ecosystem services (e.g., air, food and water processes, capture fisheries) needed by humans are now “being degraded or used unsustainably”. The World Scientists Warning to Humanity (UCS 1992) warned that humans and the natural environment are on a “collision course” and that fundamental change is required to avoid catastrophic disaster. Major environmental problems that are the focus of extensive research include 1) excess CO_2 emissions from industrial societies and their links to climate change and warming (Friedlingstein and Solomon 2005), 2) excess reactive N emissions to atmosphere and surface waters and their association with acid rain and eutrophication (Jordan et al. 2003, Galloway et al. 2003, Cowling et al. 2001, Driscoll et al. 2003), 3) loss of species and destruction or degradation of the ecosystems and habitats required for them to live (Reid and Miller 1989).

Such current human-environment problems can be characterized as *chronic* and *systemic*, and this combination may describe a novel kind of problem for humanity. Chronic describes problems that are persistent and ongoing and distinguishes current problems from ones that are transient or resolve themselves in the short term. These problems are plausibly systemic in that the impacts affect all sectors of society and the root causes are not easily isolated or attributed to one or a few offending sectors. Chronic-systemic problems resist management actions and are slow or difficult to solve. Even for solutions that seem effective in the short-term, they often exhibit diminishing returns from continued implementation of initially successful strategies. Relapse, "back-sliding" or losses of prior gains can also occur. Potential solutions are often constrained by potentially negative side-effects or unintended consequences (e.g., switching from coal to nuclear fuel for electricity generation can reduce CO_2 emissions but increase problems associated with nuclear waste disposal). Deadlines for ecosystem restoration are often missed and must be set back. Cost estimates for solutions often increase dramatically. Such dynamics can be stressful for the people and agencies working toward solutions and social conflict and turf battles may result.

The case of the Chesapeake Bay, including its smaller estuaries and tributaries and its integrated landscape, provides specific examples of most if not all of these general and unique attributes of chronic-systemic human-environment problems. The Bay is threatened by many inter-related problems, many of these appear to be chronic-systemic individually, and it may be that the whole suite of problems is itself chronic-systemic.

Excess nitrogen (N) loading from the human-dominated watershed is one of the Bay's major stressors. Eutrophication overall leads to increased phytoplankton, decreased water clarity, severe and recurrent hypoxia and declines in abundance of submersed vascular plants (Kemp et al. 2005). Other stressors include invasive species, over-harvesting of major fish, crab and shellfish stocks, habitat loss due to development, multiple forms of toxic waste, sediment loading, and increasing incidence of disease (Kemp et al. 2005, CBP 2006a). The majority of N loading comes from distributed non-point sources (e.g., agricultural and urban run-off and atmospheric deposition) compared to localized point sources (e.g., wastewater treatment plants; Blankenship 2005, Boyer et al. 2002). While N loading has declined significantly since 1985, attributable to improvements in wastewater treatment, agricultural practices and other management actions, several major tributaries have seen the rate of decline slow or stop, and for some N loading has begun to increase (Blankenship 2005). Figure 3.1 shows the trend in N concentration in the Patuxent River (monitoring site at Bowie, MD) where a plateau in reductions suggests an impasse has been reached even though further reductions are desired and required. Such trends may be explained by increased N emissions due to increased population, development and intensive agriculture offsetting hard-won N reductions due to implementation of best management practices in agriculture and wastewater treatment.

Full restoration of environmental quality for the Chesapeake Bay was once estimated to cost $19 billion (Blankenship 2002), but this estimate was later increased to $29.3 billion (Blankenship 2004). In 1987 a multi-state agreement set the year 2000 as the goal for restoration of the Bay and addressed N loading as well as problems of phosphorus, sediment, aquatic vegetation and other factors. That deadline passed and a new agreement set the year 2010 as the target to achieve water quality and other

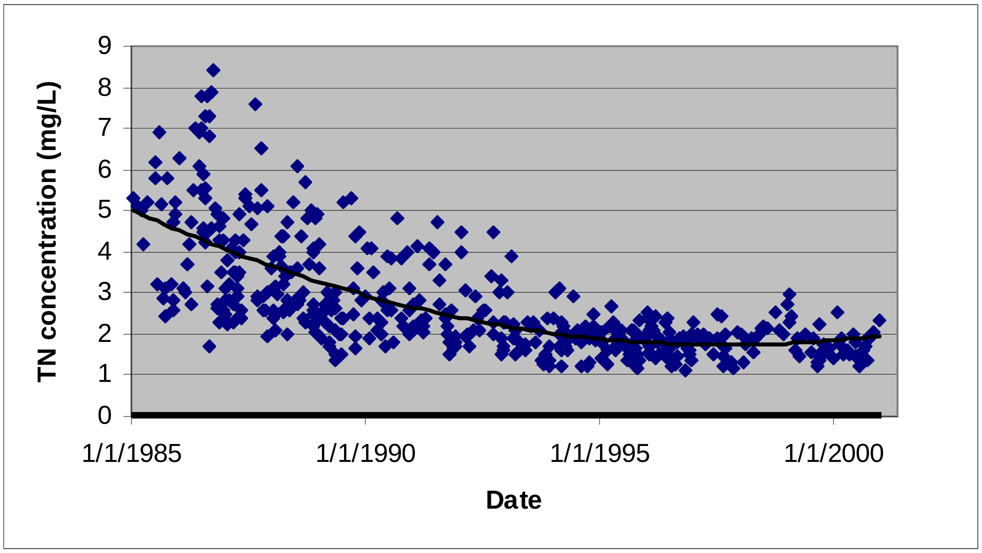


Figure 3.1. Total nitrogen (TN) concentration in the Patuxent River at Bowie, 1985-2000. Data from Chesapeake Bay Program (Fisher et al. 2005). Comparison reference level for TN levels typical from forested watersheds is shown as thick line near X-axis at 0.05 mg per liter, 40 times less than the apparent plateau at 2 mg per liter for the heavily human-dominated Patuxent watershed.

improvements and avoid the imposition of regulatory measures such as legal enforcement of total maximum daily loads. It was recently reported that the 2010 deadline will not be met either, but no revised timeline has yet been developed (Blankenship 2006). Political and public arguments over who is responsible for the Bay's problems, and who is to blame for the lack of progress, can lead to conflict between social groups and public agencies. This conflict, which is often played out in the press and other media (Williamson 2005, Whoriskey 2004, Ernst 2003), can serve to dampen hopes and raise tensions, even as it helps to increase the level of dialogue and scrutiny.

The list of problems and complexities goes on, both for the Bay and for humans in general. Excess CO_2 emissions are related to sea level rise that affects the Bay and its low-lying wetlands. Energy problems are now pressing with the impending peak in world oil production (Campbell 2005), non-renewable energy dependency, and increasing costs and economic impacts. Water is critical for human life and hygiene, and connects to flooding problems, species habitat and conservation and many other issues (Gleick 1998). Water quality and quantity are also crucial environmental issues for the Bay, and water problems are similarly persistent and pervasive throughout human activities. For example, increased run-off can be driven by increases in area of impervious surfaces and restoration timelines are strongly affected by nutrients in groundwater that can be slow to reach the Bay. The gravity and intensity of environmental problems facing the Bay and its watershed suggests that environmental science faces a difficult task to provide knowledge leading to solutions, and to help develop solutions that are truly effective over the long-term.

Given such challenges, development of novel approaches to environmental science for solution of chronic-systemic human-environment problems seems warranted.

Environmental Currencies and Sustainability

The search for novel approaches can begin with the most basic fundamentals of environmental science. Four physical, material fluxes - carbon, nitrogen, energy and water - appear as recurrent themes within human-environment problems, and these fluxes are mainstays in ecological and environmental science. These basics are central to energy flux and the material cycling, two major topics of any Ecology 101 course. The primary physical fluxes may also be seen as “currencies” - entities that are “exchanged” and also have “value” for all living systems from cells to species to humans to ecosystems. Carbon, nitrogen, energy and water are also significant for consideration in human socioeconomic terms in that they arguably are not replaceable or substitutable.

One holistic and synthetic approach to addressing chronic-system human-environment problems is environmental sustainability. Environmental sustainability can be defined succinctly as a property of any process, community or system that 1) uses renewable, net energy and 2) uses recycling materials processes. Goodland and Daly (1996) provide another parsimonious set of criteria for truly sustainable human-environmental systems in their Input-Output rules (see Chapter 1 in this dissertation for the full text of the rules). Their definition is so useful, meaningful and concise one is hard-pressed to imagine a stronger formulation. The Goodland and Daly rules may in fact encompass the *necessary and sufficient conditions for local environmental sustainability*. Such a rigorous concept could one day become the First Law of Human Ecology. For now, two major aspects of this definition of sustainability will be adopted. First, environmental sustainability will be defined and assessed with an emphasis on local supplies of key resources and local capacities for waste assimilation. Second, a qualitative assessment of sustainability can be made by comparing 1) whether emissions from a project are greater than local waste assimilation capacity, 2) if renewable resources are used faster than they are replenished by natural processes and 3) if use of non-renewable resources is accompanied by ongoing efforts to develop equivalent renewable replacement capacities. The definition and assessment of environmental sustainability will be applied with reference to uses and emissions of C, N, energy and water.

Existing Environmental Science Strategies

In the current state of the art for the physical form of environmental science itself, as we work to increase understanding, educate the next generation and solve problems, two main schools of thought exist that parallel the objective and relational challenges depicted above. Most environmental science institutions do not scrutinize their own environmental needs and impacts but focus exclusively on the generation of new objective knowledge. In contrast, a few universities and research centers have decided that the environmental demands and legacies of their own operations are crucial issues. These institutions have begun to examine, monitor and also convert their own operations to more sustainable, less consuming forms. Oberlin College (OH), the Woods Hole Research Center (MA), and the Sustainability Institute (VT) are examples.

The majority of institutions working from the objective approach often study and seek to solve more isolated, more specific human-environment problems. Even where the scope of research expands to a broad view and extends to active restoration, it usually does not result in examination of the sustainability of the ecological processes associated with environmental science itself. For example, the strategic plan of the University Of Maryland Center for Environmental Science lists four strategic directions: 1) science to support ecosystem based management, 2) multi-scale ecosystem restoration, 3) linking observing systems and forecasts from mountain to sea, and 4) regional consequences of climate change and variability (UMCES 2004). This plan has no mention of accounting for uses or emissions of C, N, energy or water from UMCES facilities. Similar emphases on objective knowledge without self-referential examination of environmental impacts are commonly observed for many other universities, research centers, government agencies and professional science societies (e.g., the National Science Foundation and the Ecological Society of America).

Turning the “Ecoscope” Inward – To Study Environmental Science Itself

The central idea proposed here is that a focused examination of the key environmental fluxes of environmental science itself, and an assessment of the environmental sustainability of these physical-environmental relations, may lead to novel insights able to stimulate quantum leaps in science and real world solutions for environmental quality. The link between self-reflexive science and progress for sustainability owes inspiration to the “post-normal science” of Funtowicz and Ravetz (1997) and multi-scale integrated analysis of Giampietro (2004). The impetus for self-reflexive science as route to problem solving originates in the hypothesis that *the subordination of environmental values to other values* (e.g., economic, social, technological or scientific) is the ultimate cause of environmental degradation. If the subordination of environmental values is systemic throughout industrial society, then it may be the shared root cause driving chronic-systemic human-environment problems. The inferiority of environmental values could be the ultimate cause that drives more visible proximate causes of environmental degradation such as those arising from technologies, agriculture, transportation, buildings and human behaviors. And if the subordination of environmental values occurs in environmental science – ostensibly the socioeconomic arena in which the importance of environmental processes and resources is best understood – then this provides evidence for its systemic nature throughout our culture.

In the attempt to catalyze a break-through in understanding and problem solving, this study explored the following questions:

1. Is environmental science outside (independent from) or inside (participating in) the major environmental problems associated with C, N, energy and water?

2. What absolute and relative amounts of C, N, energy and water are used by and emitted from environmental science compared to the supplies and capacities of the local environment? What is the local carrying or production capacity for environmental science?

3. Is environmental science environmentally sustainable? Is environmental science characterized by a) emissions rates greater than local assimilation rates, b) resource uses

faster than regeneration, or c) use of non-renewable resources without efforts to replace them with renewable substitutes?

4. What changes would be required for sustainability? What would environmentally sustainable science be like in terms of energy, C, N, and water demands as met by local supplies and waste emissions met by local assimilative capacities?

As mentioned above, two schools of thought differ in their approaches to examining versus ignoring environmental costs and the sustainability of environmental science itself. This disagreement or schism within environmental science suggests that more institutions may begin to consider this issue and may be seeking to choose between these two paths, and that additional information on these two alternatives could aid in decision making and choosing a direction and course of action. Toward these ends, the following additional corollary questions were explored:

5. What is the best environmental strategy or organizational form for the long-term success of ecological and environmental science?

6. Can sustainable ends for society in the long-term be achieved by unsustainable means and operations of science in the short-term? For example, can an end goal of low N export from a watershed be achieved via a science process operating with high N export? How do the long- and short-term relate and interact?

7. Would environmentally sustainable science be better or worse in terms of core missions of research, education, public service, and applications to management, policy and problem solving? Is it better to internalize or externalize environmental costs of doing environmental science? What are the pros and cons, costs and benefits of these two options for environmental “capital accounting”?

To answer and explore these questions research was done to quantify the C and N emissions and the energy and water uses for average annual operations for Appalachian Laboratory (AL), part of the University of Maryland Center for Environmental Science (UMCES). AL serves as a representative example of an environmental science institution, and it has been the place of employment and graduate education for the author from 1997 to the present. For comparison to the emissions and uses of AL, the project resulted in estimates of ambient, local inputs of renewable energy and water, and the local C and N absorptive capacities, for an oak-hickory forest typical of the local area and of comparable size to the area of the AL building and grounds. Original rough hypotheses were that AL was unsustainable for all four major environmental fluxes by factors of 100 to 1000. The results include both surprises and important implications for strategic plans, science practice, theory and action for understanding and helping solve the major problems of our day.

Data and Methods

Study Area and Systems Descriptions

Appalachian Laboratory (AL) is located in Frostburg, a city of 8,075 year-round residents in the Appalachian mountains of Western Maryland. Frostburg is also home to Frostburg State University, which has another 5,400 student residents. As one of four labs in the University of Maryland Center for Environmental Science (UMCES), AL shares the UMCES missions of 1) science research and discovery, 2) graduate education and 3) public service. The UMCES mission statement, “To develop a predictive ecology for Maryland”, also acknowledges a commitment to the people of the state. Faculty and staff have expertise and active research and teaching programs in aquatic ecology, landscape and watershed ecology, conservation biology and restoration ecology, behavioral and evolutionary ecology, wildlife management and other related fields.

The precursor organization to AL was founded in 1962, but the current building was designed and built in 1997-1998 and occupied in late 1998. Approximately 70 people work and study at AL, with 14 faculty, 14 staff, 21 research staff and 22 students as of summer 2006. The indoor area of the main building and greenhouse is 47,000 square feet and the buildings plus parking lots cover 2 ha. The entire property, including lawn, forest and several special planted habitats, covers about 4 ha (see Figure 3.2).

The elevation at AL is 660 meters, and it is within the Sand Spring Run, Georges Creek, North Branch Potomac River and Chesapeake Bay watersheds. AL is located on the Allegheny Plateau physiographic province. Local bedrock geology types are predominantly shales and sandstones; the area was not glaciated during the last glaciation. Coal mining began in Frostburg in the 1820’s and continues today. The AL building sits on top of underground mines that were filled prior to construction.

Figure 3.2. Aerial photo of Appalachian Laboratory building and grounds. The buildings and parking lots cover about 2 ha (box area) while the entire property is 4 ha. Image from Allegany County GIS Department (Allegany County GIS 2006).

The average annual precipitation in the local area is 1116 mm. Deciduous forest communities of oak-hickory and similar types naturally inhabit the land near AL. Trees common in the area include white, red and chestnut oaks, red and sugar maple, black locust, black walnut, several hickories, black cherry, white pine, hemlock and other important species. Black bears, white-tailed deer, ground hogs, crows, big brown bats and Eastern bluebirds are just a few of the many local animal species.

Estimates of energy, carbon (C), nitrogen (N) and water fluxes were obtained for 1) the AL building and organization as a whole, 2) human workers of AL based on generalized human physiological needs, and 3) the local environment and a typical local forest. The period of study was 1999 through 2005. Utility bills, records of faculty and staff air travel and gasoline purchase records provided the initial data for AL uses of electricity, natural gas, gasoline and water. Conversion factors found in the literature or online were used to generate estimates of energy, C, N and water fluxes that could be compared across system types, i.e., the same units used for AL buildings and equipment, human personnel and the local ambient or forest reference system. Comparisons were made both on a total flux, non-spatial basis and on a relative flux, spatial basis using 2 hectares as the area of AL for estimating fluxes per unit area. Units used were 1) kg C per year and kg C per ha per year, 2) kg N per year and kg N per ha per year, 3) megajoules (Mj) of energy per year and Mj per ha per year, and 4) gallons (gal) of water per year and gal of water per ha per year. For humans, either average or typical values for the U.S., or rough averages from several studies of people in different countries, were used.

Separate conversion methods were used for electricity, natural gas, gasoline, air travel and human respiration (see Appendix Table A6 for all conversion factors used).

Whenever possible multiple values for each emission or conversion factor were obtained and considered as independent or alternative estimates. Multiple values were averaged if alternative estimates were considered equally valid. A single value was chosen if one of the estimates or references was considered stronger. Tables in the Appendix include all estimates selected and many of the comparative estimates considered or used in derivation of the estimates.

In addition to the data on C, N, energy and water, estimates of annual publications and numbers of graduate students trained were collected.

Uses and Emissions of AL Building and Organization

AL Carbon Emissions

Estimates of AL's CO_2 and C emissions were derived from utility bills for electricity and natural gas, and air travel and gasoline purchase records, obtained with permission and assistance from AL administrative staff. In order to sum and compare several different carbon fluxes, all fluxes were converted to kg of C using a ratio of 12/44 (i.e., a factor of 0.273) for the proportion of CO_2 that is C.

Conversion factors for CO_2 emitted per megawatt hour (MWh) of electricity varied for the years of the study, as did the fuel mix of AL's electrical utility, Allegheny Power (see Appendix Table A6). Emission factors were obtained from "Energy Source (Fuel Mix)" and "Air Emissions" disclosures of Allegheny Power for 1997, 2003 and 2004. CO_2 emissions for 2000 for this utility came from EPA's eGRID database (eGRID

2006). Linear interpolation was used to estimate emissions for years between known rates. The reported CO_2 emission for 1997 was 2066 lbs per MWh and the value for 2004 was 1195 lbs per MWh (see the Results for an explanation of this drop). For comparison, the Natural Resource Ecology Lab environmental footprint study (Easter 2002) used a value of 1.64 pounds per kilowatt hr (kWh), which is equal to 1640 lbs per MWh.

A conversion factor of 5.91 kg CO_2 per therm of energy derived from natural gas was reported in the World Resources Institute (WRI) “Direct CO_2 Emissions from Fuel Combustion” spreadsheet (WRI 2006), for which they cited an Energy Information Association (EIA) 2001 report, “Emissions of Greenhouse Gases in the U.S. Appendix B”. This value was about 14% more than the 115 lbs of CO_2 per 1000 cu. ft. of natural gas combusted as reported by the U.S. Carbon Dioxide Information Analysis Center (CDIAC 2006). The WRI and EIA value was chosen for this analysis based on its use by two major organizations.

Records were obtained for faculty and staff air travel with origination and destination airports and with each trip noted as one-way or round-trip travel. CO_2 emissions for air travel were calculated using the WRI spreadsheet “Indirect CO_2 Emissions from Business Travel” (WRI 2006). This reference estimated 0.18, 0.13 and 0.11 kg CO_2 per passenger km for short, medium and long haul trips respectively. Two different web-based mileage calculators provided estimated mileages between departure and arrival airports. For domestic flights to/from major U.S. airports, an airport to airport distance calculator available online at the U.S. Office of Surface Mining was used (OSM 2006). For international flights and smaller U.S. airports, a distance calculator from Air Routing International was used (ARI 2006). Once the total distance for each flight was determined, distances for all flights in a given month were summed. These monthly total distances were then used for estimates of CO_2 emission using the above factors. The same distances were also used for estimates of NOx emission and energy use of air travel.

A conversion factor of 8.87 kg CO_2 emission per gallon of gasoline was used as reported by the WRI spreadsheet (again citing the EIA 2001 report). The NREL report (Easter 2002) used a value of 36 lbs per gallon, which is roughly double the factor used here. No attempt was made to differentiate between regular, plus or super grades of gasoline or automobile types (e.g., cars, trucks, gasoline and diesel engines in the AL fleet) for C, N or energy emissions and uses.

AL Nitrogen Emissions

As for C, nitrogen (N) emissions from electricity, natural gas, air travel and gasoline were estimated for AL as an organization. The main form of N emission was treated as NOx in general and as NO_2 in specific when needed for conversions (EPA 1998). In order to sum and compare several different N fluxes, all fluxes were converted to kg of N using a ratio of 14/46 (i.e., a factor of 0.304) for the proportion of NO_2 that is N.

As for C, the Allegheny Power fuel mix and air emissions disclosure sheets provided NOx emissions for 1997, 2003 and 2004 and the EPA eGRID database (eGRID 2006) provided the value for 2000. Also like CO_2, the NOx emissions changed (decreased) during the period of the study (1999-2005). Missing values were again interpolated assuming linear trends in changes. The values of NOx emission per MWh of electricity generated ranged from 5.6 lbs in 1997 to 2.9 lbs in 2004. (See the Discussion section for discussion of changing percentages of coal, nuclear and natural gas.)

Estimates of NOx emission from burning of natural gas in AL's boilers (for heating the building and hot water) were obtained from the Emissions Factor Information Retrieval (FIRE) database of the U.S. EPA. (WebFIRE 2006). This database reported a value of 100 lbs per thousand cu. ft. of natural gas for systems generating less than 10 million Btu per hour with no NOx emission control. John Hutchins (personal communication) of Casto Technical confirmed that AL's boilers matched this category. He also reported that the concentration of NOx in exhaust from the boilers was likely 60-70 parts per million, but no comparison of this estimate to the EPA estimate was made for lack of information on total boiler exhaust.

The process to accurately estimate NOx emissions from jet aircraft and air travel is very complicated as the emissions vary with power level of the plane (FAA 1997). Two independent estimates were found for an average value of NOx emission per passenger per unit of distance traveled, and these two values were very similar. The first estimate was obtained using data for CO_2 and NOx emissions (National Academy Press 2002), which gave a ratio of NOx to CO_2 emission of 15/3200. This ratio was used to estimate NOx emission using prior estimates for air travel CO_2 emissions yielding a value of 0.86 g NOx emitted per passenger mile. A second estimate was calculated using annual totals for air travel and NOx emissions from a NASA report (NASA 2003). This yielded an emission factor of 0.89 g NOx per passenger mile. The lower estimate was used to calculate total monthly NOx emissions from air travel using monthly flight distances.

NOx emissions from gasoline combustion and automobile engines was obtained using a value of 0.256 g per mile (Davis, S.C. and S.W. Diegel. 2002). An efficiency factor of 24.1 miles per gallon was also used to convert gallons of gasoline into an estimate of miles traveled. No comparison values for NOx emissions per vehicle mile were found.

AL Energy Use

In order to sum and compare several different energy uses, all energy was converted to units of megajoules (Mj). Separate conversion methods were used for electricty in kWh, natural gas in cubic feet, gasoline in gallons and air travel in passenger kilometers.

For electricity, a conversion factor of 3.6 megajoules per kilowatt hour (kWh) was used as reported by Energy Information Administration (EIA 2006) and Davis and Diegel (2002). The latter source stated this "…figure does not take into account the fact that electricity generation and distribution efficiency is approximately 29%. If generation and distribution efficiency are taken into account,1 kWh = 11,765 Btu". This higher estimate is equal to 12.4 Mj per kWh. The lower estimate was used, and thus this method results in a conservative or under-estimate of the total energy expenditure associated with electricity use.

A conversion factor of 1027 Btu per cu. ft. of dry natural gas was reported in Davis and Diegel (2002). This number was comparable to another value of 1031 Btu/ft^3 reported by EIA (EIA 2006). Monthly values of natural gas use reported in hundreds of cu. ft. (CCF) on bills from Columbia Gas were converted to Btu’s and then to megajoules.

Two values for the energy intensity of air travel were reported in Davis and Diegel (2002) - 4061 Btu per passenger mile for 1999 and 3952 Btu per passenger mile in 2000. An intermediate value of 4000 Btu per passenger mile was used for all years.

Monthly gasoline purchases for three different companies were combined to get total monthly gasoline use. A conversion factor of 130.88 megajoules per gallon of gasoline was then used as reported by both EIA (EIA 2006) and Davis and Diegel (2002).

AL Water Use

Monthly water bills from the City of Frostburg provided data to average annual calculate water use. These reported gallons of water used and no conversion was needed. An odd pattern of use with extreme variation could not be explained. Water use increased dramatically from 1999 to 2001, then declined sharply to a lower level of use from 2002 through 2005 (see Figure 3.3). A single monthly extreme in July of 2004 also could not be explained. Without knowledge of different conditions, anomalies or problems, the entire period was treated the same despite these extremes. No attempt was made to separate indoor from outdoor water use (i.e., watering of lawn and vegetation).

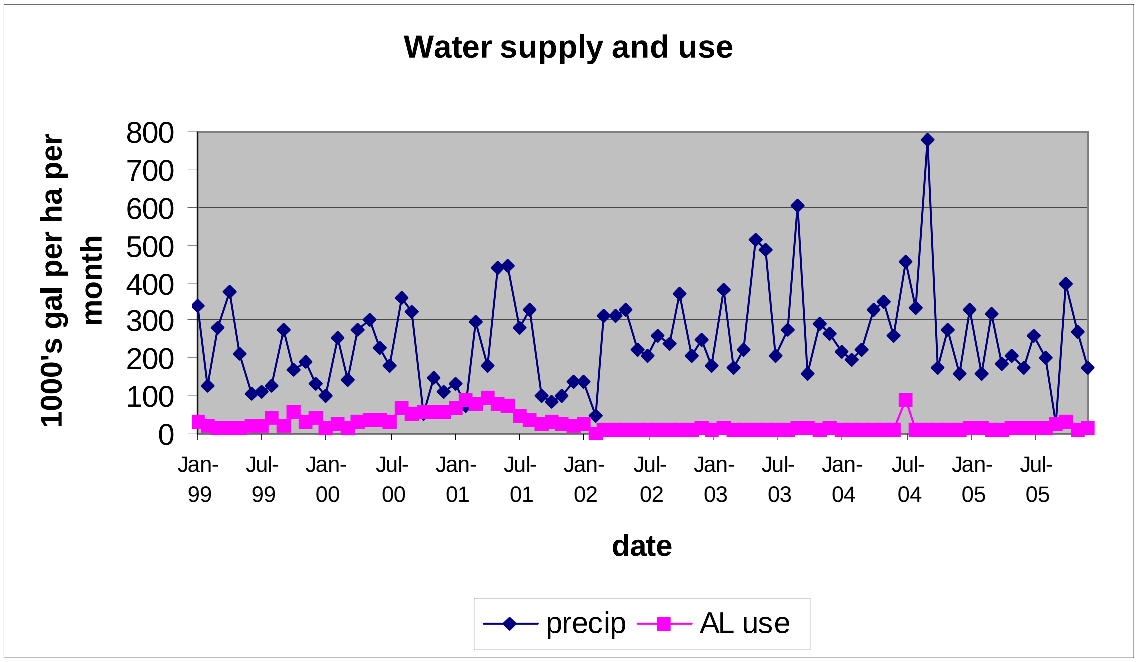


Figure 3.3. Comparison of AL water use and water supply via local precipitation (precipitation data from Latta 2006).

Human Uses and Emissions of C, N, Energy and Water

All estimates of human C and N emissions and energy and water uses were made assuming a total of 70 people at AL. A further assumption was made that one third of each person's daily needs and emissions were associated with work or study at AL based on an eight hour work day. For monthly sums, it was assumed that people worked 20 days per month and thus 240 days per year. This approach likely leads to over-estimates for regular building occupants since not all 70 people are present every day. Visitors and special events could result in periods of time when more than the 70 regular personnel are in the building.

Human CO_2 emission via respiration was estimated using several reports in the literature. Values ranged from 0.84 to 1.2 kg per person per day (Taub 1974, Czupalla et al. 2005). An intermediate value of 1 kg per person per day was used for this analysis. These assumptions resulted in a constant value of 466 kg per month for human CO_2 emissions for all personnel combined. Exports of C in sewage was estimated to be about 72 kg/yr (i.e., 5% of the respiration CO_2 amount) but was not included in the analysis.

Human nitrogen fluxes were estimated using an average of several values reported for both ingestion of N in food and excretion of N in urine and feces. All reports assumed or documented average daily N balance for adult humans such that inputs in food were matched by excretion over time. Reported values ranged from 7.53 g/day (Gajdos 1998) to 15.6 g/day (Heinonen-Tanski and van Wijk-Sijbesma 2005). An intermediate value of 12 g/day was used to estimate daily export of N per person. These assumptions resulted in a constant value of 5.59 kg per month for human N emissions for all personnel combined.

Human energy use was estimated using a rough estimate of 2500 kilocalories (kcal) of food energy per person per day (note that dietary calories on food labels are energy kilocalories). This is equal to 10.5 megajoules (Mj) per day of human energy use. This value was chosen as intermediate between comparison values of 2002 kcal per day (or 8.4 Mj per day) for a U.S. national average for 1994-1996 (USDA 1998) and 2823 kcal per day (11.8 Mj per day) for NASA astronauts (Hanford 2004).

Daily drinking water consumed at AL for human physiological needs was estimated to be 0.85 kg per person per work day or 0.22 gal per person based on the International Commission on Radiological Protection (Snyder et al. 1974). Comparison values ranged from 0.8 (Taub 1974) to 1.3 (Hanford 2004) kg per person per 8-hour day.

An attempt was made to estimate human non-dietary or hygienic water use, but a satisfactory method was not found. A map on an EPA water information website (EPA 2006) showed a value of 171 gallons per person per day total water use for the Mid-Atlantic area. This combines commercial and residential, but the site also reports that residential uses are 57% and commercial uses only 15% of the total. Of the residential uses 33% is estimated to be for bathing, 21% for washing and laundry, 41% for toilet and 5% for kitchen. Adjusting the estimated total water use for an 8-hour work day and taking 25% of that assuming relatively low water use resulted in a value of 19,852 gallons per month total for human hygienic water use. This value sometimes exceeded the actual total AL monthly water use and resulted in an estimate of hygienic water as 38% of the AL total. In absence of an approach yielding more realistic estimates, no estimate was made for hygienic water use.

Local Ambient and Forest Reference Capacities

Standards for comparison of the AL organizational and human fluxes of C, N, energy and water were estimated based on the local environment. This approach is similar to ecological footprint analysis (Wakernagel et al. 1999), which estimates “biocapacity” as the basis for assessing human impacts and sustainability. The approach taken also borrows from the general principles of sustainability in the input-output rules of Goodland and Daly (1996). The latter states that environmental sustainability requires that “waste emissions from a project must be within the assimilative capacity of the local environment to absorb without unacceptable degradation of its future waste-absorptive capacity or other important services.” Specifically noting the “local” aspect of this definition, the C and N assimilation, retention or sequestration capacity of a typical, local, deciduous forest were treated as appropriate comparisons for assessing the sustainability of AL’s C and N waste emissions.

For AL’s organizational and human energy and water needs or demands, the local supplies of energy and water via solar and wind energy and precipitation were estimated as reference bases for sustainability. The reference to local solar and wind energy is not meant to imply that conversion to such energy sources is necessarily possible or desirable. This comparison amounts to a preliminary and general comparison of the magnitude of AL energy use – most of which currently is derived from *non-renewable* natural gas, coal and oil resources that come from *distant* reserves - relative to *renewable* supplies potentially available *locally*. This comparison does not address any economic, political or logistical issues associated with the differences in the options for energy supply.

Forest C Sequestration Capacity

Many literature values, and one value calculated via spreadsheet model, for carbon sequestration by forests typical of the area were found and compared. Values for annual C uptake in forests ranged from a low of 600 kg C per ha as average for all U.S. forests (Dixon et al. 1994) to a high of 5850 kg C per ha for oak-hickory forest in Walker Branch, TN (Malhi et al. 1999). Schmid et al. (2000) reported an annual range from 2000-5000 kg C per ha in Harvard Forest in Massachusetts. Niu and Duiker (2006) reported a potential or maximum rate for forests in Maryland as 3600 kg C per ha. Use of a spreadsheet tool available online from The Nature Conservancy (TNC 2006) yielded an estimate of 4500 kg C per ha when the aboveground estimate was doubled to account for annual C sequestration in soils. An intermediate annual value of 3000 kg C per ha was chosen for this analysis. Additional estimates are reported in Appendix Table A3.

Forest N Retention Capacity

Many literature values for nitrogen retention by forests typical of the area were found and compared. Estimates of atmospheric N deposition (both pre-industrial and current rates) and biotic N-fixation also were considered as means of constraining an estimate of a reasonable N retention capacity. As in the Goodland and Daly (1996) principle above, an important consideration became the waste assimilation capacity achievable “without unacceptable degradation of its future waste-absorptive capacity or other important services”. The observation of a threshold of annual atmospheric N deposition of 7-10 kg/ha above which forested and other watersheds begin to export NO_3 via streams was treated as crucial (Aber et al 2003). A value of 8 kg/ha was used as a safe or precautionary N retention capacity assuming that higher values could plausibly result in degradation of the future capacity of the forest to absorb N due to declines in forest productivity or leaching of key cations such as calcium. This value was also intermediate for the range of estimates of 7.1 to 9.2 kg C per ha for N uptake into live wood in forests in the Northeast U.S. (Goodale et a. 2002) Additional estimates are reported in Appendix Tables A1 and A2.

Ambient Energy Supplies

To estimate the solar energy incident on the AL building and grounds, two independent estimates were obtained and compared. Data from the Surface Radiation network downloaded for the Pennsylvania State University (PSU) site (SURFRAD 2006) provided actual measurements for a site about 100 km northeast of AL and thus likely receiving similar solar radiation. These data yielded an average of 3.7 kWh/m^2/day for total solar radiation for the PSU site. Photosynthetically active radiation (PAR) averaged 1.6 kWh/m^2/day. This data covered 1999-2005 time period. See Figure 3.4 for monthly variations in total solar radiation.

National Renewable Energy Laboratory's (NREL) PVWATTS program was used to estimate solar energy potentially available from photovoltaic collectors (NREL 2006). This gave 4.66 kWh/m^2/day for Baltimore, MD, which is about 240 km to the east. This estimate assumed a flat panel solar array facing south with a fixed tilt equal to the latitude of Baltimore (39 degrees). On this same website, a map of the solar energy resource for U.S. gave a value of 4.5 kWh/m^2/day for Western Maryland assuming the same flat, south-facing array tilted equal to the latitude. An intermediate value between the PSU

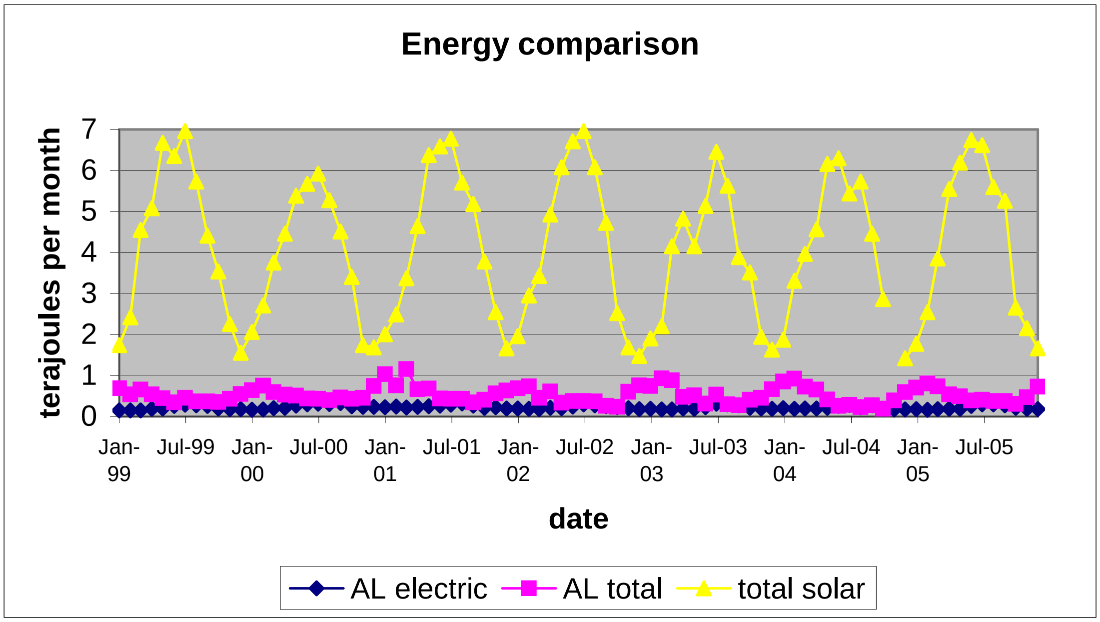


Figure 3.4. Comparison of monthly AL electricity energy, total building energy use (electricity plus natural gas) and monthly total solar radiation at Penn. State University monitoring site (SURFRAD 2006). All measures are on a per ha basis. Measures of emergy (energy quality) would improve this comparison.

(measured) and Baltimore (modeled) total solar radiation estimates - 4.1 kWh/m^2/day (i.e., 1500 kWh/m^2/year) - was chosen for this analysis.

These estimates for solar radiation were also cross-checked using studies of solar radiation and production in forests. Ahl et al. (2004) reported an average value of PAR of 1953 Mj/m^2/year for 1999 and 2000. This translates to 5.3 Mj/m^2/day or 1.5 kWh/m^2/day. This was very similar to average daily PAR from PSU, 1.6 kWh/m^2/day (SURFRAD 2006).

Estimates of wind energy potentially available near Appalachian Lab came from the National Renewable Energy Laboratory's (NREL) Wind Atlas (Elliot et al 1986). This atlas includes maps of average annual wind speed and average annual wind power density. Several areas on the ridge crests near Frostburg are rated as class 3 or higher. The NREL Wind Atlas states that class 3 and above is suitable for wind turbine applications, but the U.S. Energy Efficiency and Renewable Energy Program's "Wind Basics" website (EERE 2006) states that only class 4 and above is feasible for wind power generation with present technology. Using the upper limit of the class 3 power density range, 200 W/m^2, and assuming that this average annual wind power density is available all hours of the day gives an estimate of 5 $kWh/m^2/day$ potential wind energy. The area in this estimate refers to a vertical plane, the vertical area swept by the blades of the wind turbine as oriented perpendicular to the direction of wind (Elliot et al 1986). Actual wind energy varies significantly with time of year and time of day.

Ambient Water Supply

To estimate average annual water supply from precipitation, data were obtained from the weather website of Frostburg State University Professor Greg Latta for 1999-2005 (Latta 2006). This data provided an estimate of average annual precipitation of 1116 mm per year. This is comparable to other reports such as Kline et al. (2000) for the nearby Youghigheny basin (45.9 inches = 1166 mm), 1023 mm for the Ridge and Valley province to the east, 1216 mm for the Allegheny Plateau province to the west (Chastain and Townsend 2004), and 1110 mm for Oakland, MD, also to the west (Castro and

Morgan 2000). An estimate of the total volume of precipitation per hectare of land area was calculated assuming this average annual rainfall of 1116 mm fell on every unit of area. See Figure 3.3 for monthly variation in precipitation as converted to gallons per hectare.

Results

Average annual carbon and nitrogen emissions and average annual energy and water uses of Appalachian Laboratory from 1999 to 2005 are presented in Table 3.1 (for the mechanical, non-living sub-system) and Table 3.2 (for the human sub-system). Also in Tables 1 and 2 are AL emissions and uses as compared to estimated forest C and N assimilation capacities and local ambient supplies of solar energy and water from precipitation.

These comparisons show that AL's emissions (total of direct, local and indirect, remote emissions) from building and equipment of nitrogen (from NOx) and carbon (from CO_2) exceed the assimilation capacity of a generalized local oak-hickory forest ecosystem by factors of 57 and 70 respectively. In contrast, AL's total building and equipment energy use is less than the ambient solar energy incident on the lab building and grounds. The area of land needed to capture energy equivalent to AL's total needs is just 0.26 ha total or 0.13 ha per unit area of AL. Similarly, AL's total water use is less than ambient precipitation. The area of land needed to capture water equivalent to AL's total annual needs is just 0.13 ha total or 0.07 ha per unit area of AL.

Table 3.1. Carbon, nitrogen, energy and water uses/emissions for Appalachian Laboratory and use or emission intensity relative to a local forest reference system. These are average annual amounts 1999-2005 for the mechanical, non-living sub-system only, except for water, which includes human drinking and hygienic water. Areal, per unit area emissions are based on AL area of 2 ha. All carbon is from CO_2 emissions from building and travel. All nitrogen is from NOx emissions from building and travel. C and N intensity factors overall tell hectares of forest required to absorb or assimilate all C or N emitted by AL in one year. They are calculated as the ratio of AL emission / forest uptake, or AL use / local ambient supply.

Resource use or emission	Amount
Total carbon emission (kg C yr^{-1})	422,205
C emission per unit area (kg C ha^{-1} yr^{-1})	211,103
Forest carbon sequestration (kg C ha^{-1} yr^{-1})	3,000
C intensity factor overall (ha of forest)	141
C intensity factor (ha of forest per ha AL)	70
Total nitrogen emission (kg N yr^{-1})	910
N emission per unit area (kg N ha^{-1} yr^{-1})	455
Forest nitrogen uptake (kg N ha^{-1} yr^{-1})	8
N intensity factor overall (ha of forest)	114
N intensity factor (ha of forest per ha of AL)	57
Total energy use (Megajoules yr^{-1})	14,113,542
Energy use per unit area (Mj ha^{-1} yr^{-1})	7,056,771
Local ambient solar energy (Mj ha^{-1} yr^{-1})	54,000,000
Energy intensity factor overall (ha of solar land)	0.26
Energy intensity factor per unit area (ha of solar land per ha of AL)	0.13
Total water use (gal yr^{-1})	392,159
Water use per unit area (gal ha^{-1} yr^{-1})	196,079
Local ambient precipitation (gal ha^{-1} yr^{-1})	2,948,171
Water intensity factor overall (ha of precip. land)	0.13
Water intensity factor per unit area (ha of precip. land per ha of AL)	0.07

Table 2. Carbon, nitrogen, energy and water uses/emissions for Appalachian Lab and use or emission intensity relative to a local forest reference system. These are average annual amounts 1999-2005 for the human, living sub-system only (see notes about water estimates). Human water use is drinking water only (70 people, 1/3 of daily needs). Human C is CO_2 emission from respiration; C in sewage is about 72 kg/yr or 5% of CO_2 from respiration and is not included here. Human N is N in sewage. Human energy is food energy assuming 2500 calories per day per person (70 people, 1/3 of daily needs).

Resource use or emission	Amount
Total human carbon emission (kg C yr^{-1})	5,594
Human C emission per unit area (kg C ha^{-1} yr^{-1})	2,797
Forest carbon sequestration (kg C ha^{-1} yr^{-1})	3,000
C intensity factor overall (ha of forest)	1.86
C intensity factor (ha of forest per ha AL)	0.93
Total human nitrogen emission (kg N yr^{-1})	67
Human N emission per unit area (kg N ha^{-1} yr^{-1})	34
Forest nitrogen uptake (kg N ha^{-1} yr^{-1})	8
N intensity factor overall (ha of forest)	8
N intensity factor (ha of forest per ha of AL)	4
Total human energy use (Megajoules yr^{-1})	58,531
Human energy use per unit area (Mj ha^{-1} yr^{-1})	29,266
Local ambient solar energy (Mj ha^{-1} yr^{-1})	54,000,000
Energy intensity factor overall (ha of solar land)	0.0011
Energy intensity factor per unit area (ha of solar land per ha of AL)	0.0005
Total human drinking water use (gal yr^{-1})	3,769
Human water use per unit area (gal ha^{-1} yr^{-1})	1,884
Local ambient precipitation (gal ha^{-1} yr^{-1})	2,948,171
Water intensity factor overall (ha of precip. land)	0.0013
Water intensity factor per unit area (ha of precip. land per ha of AL)	0.0005

Comparing the relative roles of AL's mechanical and human subsystems shows that less than 1% of the CO_2 emission and about 7% of the N emission come from the human workers at AL (Table 3.3). Less than 1% of the energy use is due to human food consumption. Thus the mechanical sub-system accounts for 99% and 93% of C and N emissions respectively and 99% of the energy use. Human drinking water was estimated to be 1% of AL's total water use. Human hygienic water use was not estimated but is likely much greater than drinking water use.

Results in Table 3.4 indicate that the vast majority of mechanical C and N emissions and energy use are associated with the AL buildings and on-site equipment (although note that for electricity use actual emissions occur at remote sites of generation). About 6% of carbon and nitrogen emissions and 11% of energy use come from automobile and air travel. Energy use for buildings and equipment is from natural gas predominantly (51%) indicating that winter heating and hot water are the most energy-intensive aspects of the buildings. Electricity is the next largest energy type (38%) and its seasonal increases in the summer (Figure 3.5) suggest a large portion of this is due to summer cooling. Automobile travel uses 6.2% and air travel 4.8% of AL total energy uses.

Nitrogen emissions (NOx) from electricity use (83.9%) dominate total N emissions from the mechanical sub-system followed by natural gas (10.1%), air travel (4.6%) and automobiles (1.4%) (Table 3.4). Human N emissions are 6.9% of the total and thus exceed the emissions from automobiles and air travel. Carbon emissions are dominated by CO_2 from electricity use (68.2%) followed by natural gas (26%), automobiles (3.8%) and air travel (1.9%).

Table 3.3. Comparison of resource uses and emission from exosomatic (mechanical) and endosomatic (human) sub-systems. Endosomatic (human) water use is drinking water only (70 people, 1/3 of daily needs). Exosomatic water includes human hygenic water and was calculated by difference. Human C is CO_2 emission from respiration; C in sewage is about 72 kg/yr or 5% of CO_2 from respiration and is not included here. Human energy is food energy assuming 2500 calories per day per person (70 people, 1/3 of daily needs).

Resource Use or Emission	Total	Exosomatic (mechanical)	Endosomatic (human)	Percent Exosomatic	Percent Endosomatic
Carbon emission (kg C yr^{-1})	423,731	422,205	1,526	99.64	0.36
Nitrogen emission (kg N yr^{-1})	977	910	67	93.13	6.87
Energy use (Mj yr^{-1})	14,172,073	14,113,542	58,531	99.59	0.41
Water use (gal yr^{-1})	392,159	388,390	3,769	99.04	0.96

Table 3.4. Appalachian Lab resource uses or emissions by fuel or activity type. Percentages for the exosomatic, mechanical sub-system only. Average annual uses and emissions 1999-2005.

	Electricity	Natural Gas	Gasoline, Auto travel	Air travel	Building Total	Travel Total
Carbon emission	68.2	26.0	3.8	1.9	94.3	5.7
Nitrogen emission	83.9	10.1	1.4	4.6	94	6.0
Energy Use	38.0	51.0	6.2	4.8	88.9	11.1

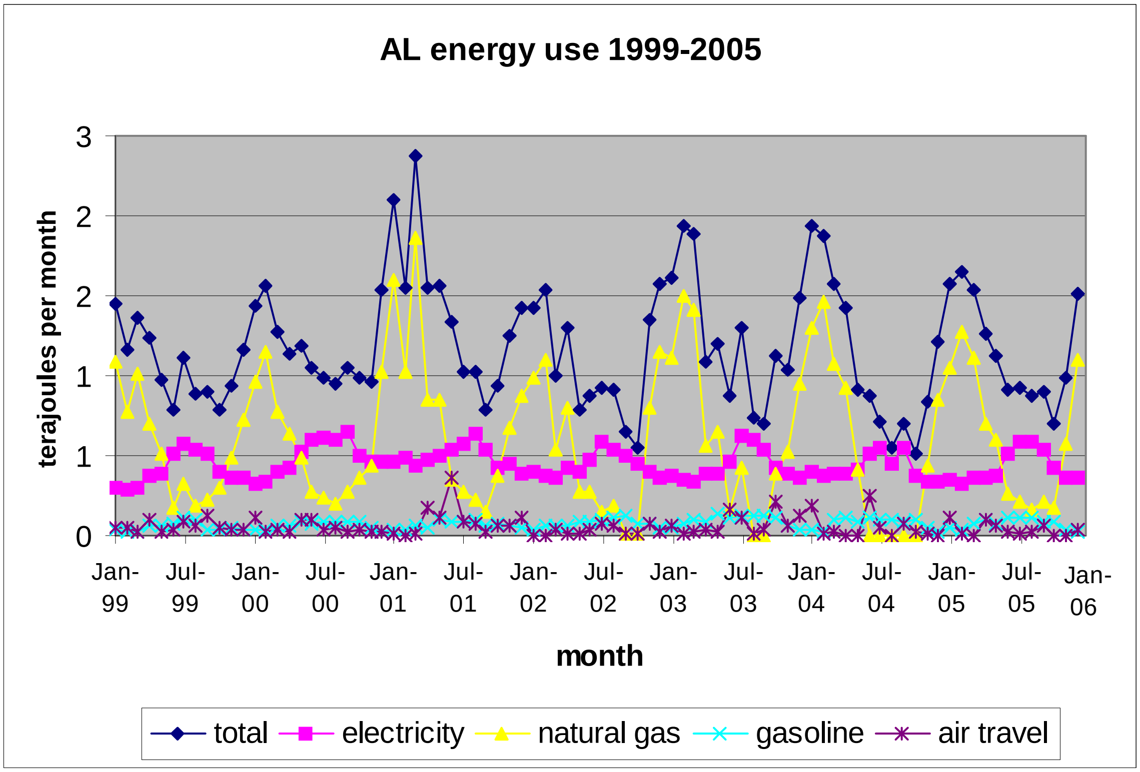
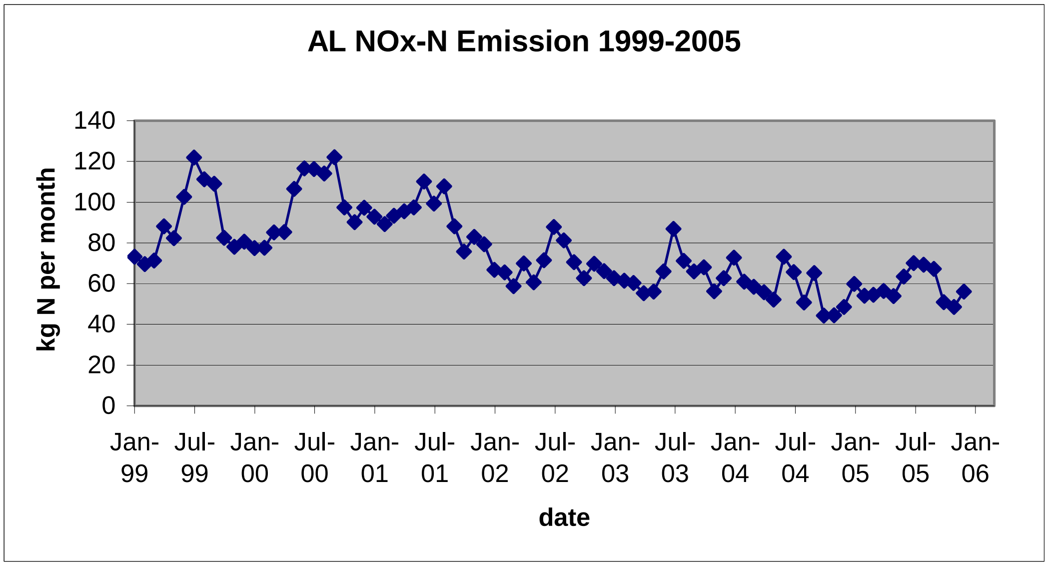
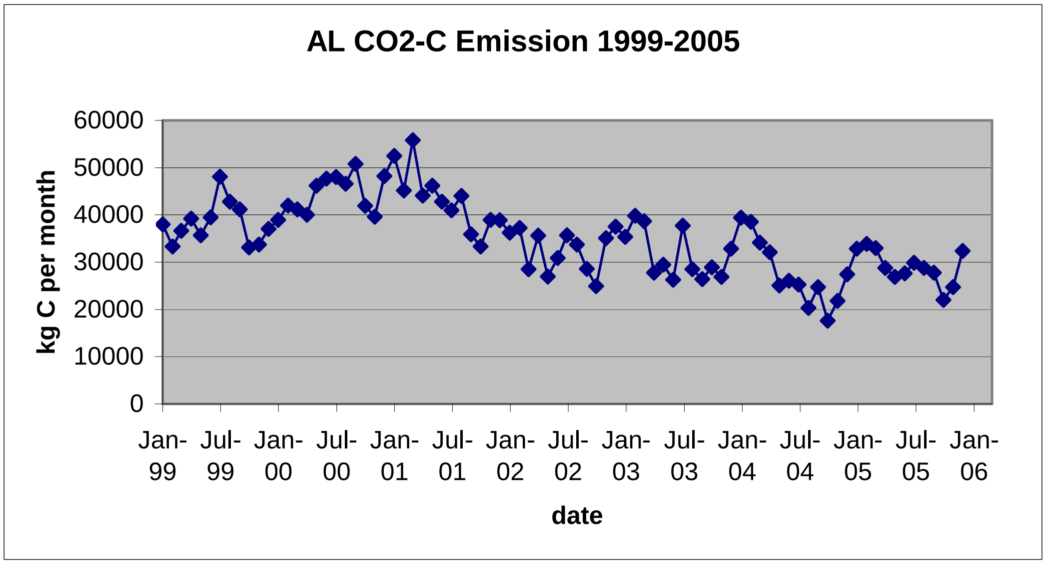


Figure 3.5. Comparison of total energy use, electricity, natural gas, gasoline and air travel, all in units of terajoules per month (total for 2 ha AL area). Note the opposite seasonality of natural gas (winter heating) and electricity (summer cooling).

Looking at trends over time, Figure 3.6 shows monthly emissions by AL of carbon and nitrogen from 1999 to 2005. Both emissions appear to trend down, and these trends are likely due to steady decreases in the percentage of coal and increases of nuclear power in the fuel mix of Allegheny Power (see Table A6 in the appendix). Figures 3.3 and 3.4 compare AL uses of energy and water to local ambient resources. Solar energy estimates came from measurements at the Pennsylvania State University's surface radiation monitoring site (SURFRAD 2006) and precipitation from Frostburg State University's





Figures 3.6A and B. Total nitrogen emission in NOx and total carbon emission in CO_2 due to the activities of Appalachian Lab. These are total emissions, not per unit area. For reference, a rough estimate of average monthly N retention in forests would be less than 2 kg, and average monthly C sequestration would be about 250 kg C, for a forest of the same 2 ha size.

weather website (Latta 2006). Both of these plots show AL uses and local ambient supplies on per unit area (per ha) basis.

The relative and dynamic roles of electricity, natural gas, gasoline and air travel in AL energy uses are depicted in Figure 3.5. This plot shows different seasonality in peaks for heating and hot water (natural gas) versus cooling and equipment use (electricity) and how the main signal of natural gas use dominates the total energy use.

Results, estimates and conversion factors taken or derived from literature values are reported in the tables in Appendix A. These include all estimates found, considered and used related to 1) ambient atmospheric N deposition and N input estimates; pre-industrial and current, 2) N uptake by forests for estimates of N retention capacity, 3) C uptake by forests for estimates of C sequestration capacity, 4) human C, N, energy, water uses and emissions, 5) local ambient solar and wind energy estimates, and 6) conversion factors used to convert various measures (e.g., electricity use to CO_2 emission).

Based on the 2004 Allegheny Power fuel mix and emissions disclosure, 2.3% of AL's electricity energy is derived from renewable sources. This includes 1.3% from hydroelectric, 0.6% from solid waste, 0.2% from captured methane and 0.1% from wind power sources. Given that electricity is 38% of AL's total energy supply (for the mechanical sub-system), and that the remaining natural gas, gasoline and jet fuel sources are all non-renewable, AL's energy comes from less than 1% renewable and thus more than 99% non-renewable resources.

Uses and emissions of C, N, energy and water were estimated relative to the major AL products of articles published and graduate students trained. In the 1999-2005 period, 32 masters and doctoral students graduated from either University of Maryland or

Frostburg State University that had a major faculty advisor at AL (Paulette Orndorff, personal communication). This resulted in an annual average of 4.6 graduates per year, which was rounded up to 5 for use in estimating per-student environmental fluxes. This yielded annual values of 84,441 kg C emission, 182 kg N emission, 2,822,708 megajoules of energy use, and 78,432 gallons of water use per graduate student completing a degree.

During the study period, faculty and others at AL published 159 articles, reports and chapters in books based on the online publications databases at AL and UMCES (UMCES 2006). For 1999 and 2005 additional publications were counted based on searches of the ISI Web of Science (http://isiknowledge.com). This amounts to 23 publications per year, but this number was rounded up to 25 to account for additional publications likely not included in the databases. Accordingly, this study estimates that AL emits 16,888 kg C and 36 kg N and uses 564,542 megajoules of energy and 15,686 gallons of water per published science article per year.

Conclusions and Discussion

Conclusions

The questions of this study were raised with hopes of both improving the quality of environmental science and improving the ability of environmental science to deliver on its potential to help solve the major, chronic, systemic environmental problems now facing citizens of the Chesapeake region as well as most developed societies. The approach is not intended to detract from the importance of discovery of new objective knowledge. Nor is the intent to accuse, attack or disqualify environmental science from providing information or opinions pertinent to such environmental problems or their solutions. One might consider comparing this situation to the identification of a “conflict of interest” of a judge presiding over a legal case. But unlike a legal instance where a judge may recuse himself or herself and be replaced by a more objective judge, in the case of environmental problems there is no other more objective party that could fill in. To consider key environmental problems as systemic entails a view that no party is any less in conflict of interest. From this perspective, society has no alternative but to help improve environmental science, and it is up to environmental science to take the lead, be self-critical and actively work to improve itself.

Several important qualitative conclusions can be made based on the quantitative results of this study. First, using the reference of local, natural waste assimilation capacities, nitrogen (NOx) and carbon (CO_2) emissions of Appalachian Lab are *unsustainable* by a factor of 57 and 70 respectively (following the Goodland and Daly (1996) definition for sustainability as emitting less than the local waste absorbing capacity). Thus, for example, it would take approximately 57 ha of forested land per ha of AL to absorb all the NOx-N emitted by AL annually. This same conclusion can be stated in terms of time - it would take on the order of 57 years for a forest of the same size as AL to safely absorb all the NOx-N emitted by AL in one year. For the criterion of non-renewable resources, it likewise must be concluded that the science operations of AL are unsustainable, since AL uses non-renewable natural gas, coal and petroleum-derived energy sources and does not set aside any resources for the development of equivalent renewable energy capacity.

Considering that the problems of 1) excess N loading from land to water and 2) excess CO_2 emissions to the atmosphere similarly can be defined as cases in which emissions exceed natural assimilative capacities, we can conclude that AL is inside, part of, or participating in the real systems contexts of these major human-environment problems. Admittedly, spatial scales need to be addressed for this categorical conclusion to be valid. Excess N loading is more readily defined as a rate of N export from a watershed greater than the amount that can be absorbed and processed by a water body without undesirable side-effects such as algal blooms and associated hypoxia and myriad other problems.

To bridge sustainability and the chronic-systemic problem definitions between the larger global and watershed scales and the smaller organizational scale of the AL building and grounds (2 ha) three main principles would appear to suffice. First, for the example of reactive nitrogen, we must accept that everything that goes up (is emitted) must come down (results in deposition and loading). For CO_2 this principle might be stated as what goes up (is emitted) stays up (adds to the shared commons of the atmosphere), thus affecting all. Second, we need to assess the variety and relative assimilation capacities of differing local natural environments. For example, if wetlands can assimilate more N than forests, and if wetlands are more abundant in the overall watershed than forests, then some allowance might be made for locally excessive emission knowing that the excess can be readily processed by the greater downstream assimilation capacity. Third and finally, we could consider a watershed-wide or global spatial extension of comparative local sustainability (i.e., emission rates less than local assimilation capacities). By this principle, for example (and other things equal), if we extended AL's 70-fold greater CO_2 emission than forest sequestration capacity to the entire Chesapeake Watershed, we would need an area of forest 70 times as big as the watershed to assure sustainability and prevent environmental problems. This logic seems to hold even given that excess CO_2 emission is usually considered a global imbalance.

For the task of placing or locating AL relative to the excess N problem of the Chesapeake watershed, these three principles would appear to span the scales and uphold the general assertion that AL is inside and participating in the problem. What we emit or cause to be emitted will come down as deposition, either on the Chesapeake watershed or on some other area. While wetlands and other ecological communities may well be able to assimilate more than 8 kg / ha / year, and often much more, it is not likely that any can assimilate the 455 kg / ha / year emitted by AL. For example, Lusby et al. (1998) reported daily rates of denitrification that scale up to annual rates between 31 and 168 kg per ha for grey willow and Typha wetlands. But the wetlands that do process and denitrify more reactive N than forests are not nearly as abundant in spatial extent. Of the 66,000 square miles of the Bay and its watershed, forests cover 60%, agriculture 28% and developed lands 3.6%, with wetlands only 2.6% (CBP 2006b). Thus no allowance for excessive N emission seems defensible as the excess cannot be assumed to be processed by greater natural capacities downstream. The same seems true for CO_2 emissions – no downwind C sequestration capacity greater than that of oak-hickory forest is likely to exist, so no allowance seems justified to compensate for AL's 70-fold greater than sustainable C emissions.

The same conclusions of unsustainability and “insider” status hold for the chronic-systemic societal problem of unsustainable energy use, since AL relies on non-renewable fossil fuels for 99% of its energy needs. Thus AL, and by extension all institutions of environmental science that share AL’s reliance on non-renewable energy and heavy use of energy supplies associated with high emissions of NOx and CO_2, is not physically outside, separate from or independent from these problems and their real systems contexts.

Looking at finer details of the two major sub-systems within AL, the data support the distinction that the non-living, mechanical sub-system of AL is highly unsustainable, whereas the human sub-system is potentially fully sustainable (locally, environmentally) for energy and water and not too far from sustainable for carbon and nitrogen. AL’s energy needs could be met by local solar energy and nearby wind energy (although note that this conclusion does not address economic and other major logistical issues). And AL’s water needs could be met by capturing local precipitation (however, this does not address water-related issues such as the area of impervious surfaces of AL’s parking lot and buildings). Table 3 shows “exosomatic” or mechanical versus “endosomatic” or human emissions of C and N and uses of energy and water.

Given that AL’s non-renewable energy dependency is now 99%, and that there is no known replacement for fossil fuels in terms of energy quality (Odum and Odum 2001, Heinberg 2004), it can be concluded that AL will likely need to reduce overall energy use. Similarly, we can suggest other changes required for sustainability and limits or rates characterizing a solution domain or context in which problems are solved and no longer occur. In the same way the local carrying capacity for science as specific to western

Maryland can be estimated. An environmental science operation that emitted no more than 3000 kg / ha / yr of CO_2 and 8 kg / ha / year of N would be sustainable and would not participate in chronic-systemic problems of excess CO_2 and excess N. Local renewable energy is abundant, but its use would require conversion of 99% of AL’s current fossil fuel basis to solar and wind energy. The geographic location of AL receives approximately 15 million kWh per ha of solar energy annually – nearly four times as much energy as AL’s total annual needs. The area also receives nearly 3 million gallons per ha of precipitation annually – eight to nine times more than AL’s total water use. Thus no changes in water use would be required due to locally abundant precipitation.

Results support the central hypothesis that subordination of environmental values is a root cause of chronic-systemic human-environment problems. The data are consistent with an explanation that we at AL have collectively and individually decided that our professional priorities of published articles, trained graduate students, discovery of knowledge, and public service via consulting are more important than environmentally sustainable operations. While science, education, discovery and consulting are clearly vital to society, it seems that to subordinate environmental sustainability to these goals is part of a shared, systemic and problematic worldview that also exists in sectors like transportation, energy, healthcare, industry and commerce. Workers and citizens in all these sectors may similarly decide or argue that their works and missions are important enough for society in the long-term that they warrant excessive consumption and waste emission, and the off-loading of the costs and consequences to the larger community and future generations, in the short-term. The good news is that the present study puts us “all in the same boat", and this common dilemma may provide a basis for empathy, cooperation and coordination to find and implement lasting solutions.

To adopt a new goal and value of local environmental sustainability entails a principle of fitting science to the particulars of a local environment. This in turn requires that the operational, physical form of science be largely dependent on details of the local context, which varies widely from place to place. Much like variations between the form of forests in tropical, temperate and boreal regions, science integrated with and sustainable in local environments would seemingly need to change form in concert with the real environmental context in which the science is conducted. This same principle of physical compatibility with the local environment may be applicable to all other sectors and may be central to lasting solution of chronic-systemic human-environment problems.

Discussion

Qualifications

In general the analyses reported here were conservative. Several other known AL energy and materials fluxes were not quantified or used in the comparison to local forest or ambient capacities. Known factors not analyzed include bulk diesel fuel purchased occasionally that powers the back-up generator, all of the paper and related supplies, electronic waste of computing equipment and hazardous wastes from laboratory materials. Commuting of personnel between home and work also was not considered. These are real energy and materials uses with real CO_2, NOx and other emissions that are associated with the ongoing operations of AL and many similar environmental science organizations. On the positive side, additional data exists on recycling of office paper, plastic, cans, batteries, vehicles and surplus computing equipment at AL. These data were not included for lack of processes for comparing units related to fluxes of C, N, energy and water.

One of the positive trends observed – the slight declines in CO_2 and NOx emission from 1999 to 2005 – seem likely due to the changing fuel mix for Allegheny Power (Figures 3.6A and 3.6B). The values of NOx emission per MWh of electricity generated decreased from 5.6 lbs in 1997 to 2.9 lbs in 2004 and CO_2 emissions decreased from 2,066 to 1,194 lbs per MWh. During this time the percentage of coal in the fuel mix decreased from 94.3% to 52.6% as offset by major increases in nuclear (up to from 0% to 37.2%) and natural gas (up from 0.1% to 6.9%). Thus some of the decreases in emissions are at the expense of increasing use of nuclear power, for which the environmental impacts of radioactive waste and reactor accidents are potentially even worse.

It should be noted that the conversion factor for estimating the energy associated with electricity use leads to a significant under-estimate. Davis and Diegel (2002) stated the conversion factor of 3.6 megajoules per kWh "…does not take into account the fact that electricity generation and distribution efficiency is approximately 29%. If generation and distribution efficiency are taken into account, 1 kWh = 11,765 Btu" or 12.4 megajoules. Use of the lower estimate results in a conservative or under-estimate that is just 29% of the total energy expenditure associated with electricity. Another interesting estimate is that air travel results in more than 3 times as much NOx emission as automobile travel on a per passenger mile basis.

An organization of similar size and mission as AL, the Natural Resource Ecology Laboratory (NREL) at Colorado State University conducted a similar audit of their own operations and reported the results in 2002 (Easter 2002). They reported that NREL with its the seventy-nine employees produced 1,272 tons of CO_2, which is equal to 315,308 kg C per year. This is roughly 25% less than AL's 422,305 kg C average annual emission. NREL's C emissions came from electricity use (739 tons or 58%), transportation (452 tons or 36%) and natural gas for heating and hot water (75 tons or 6%). In comparison AL's C emissions were estimated to be 68% from electricity, 26% from natural gas, and only about 6% from travel (see Table 4). These major differences suggest possible differences in conversion factors as well as actual operational emissions. For example, the NREL emission factor for gasoline was 36 lbs of CO_2 per gallon (16.3 kg / gal) while the factor used for AL was 8.87 kg / gal (WRI 2006). NREL staff also appear to do more international air travel, including significant travel to Antarctica. Unlike the present study of AL, the NREL report included energy and CO_2 impacts of commuting travel between work and home.

The NREL report estimated that electricity use mainly was due to science lab equipment (329,000 kWh per year or 36%), air conditioning (196,000 kWh per year or 21%), lighting (178,000 kWh per year or 19%) and office and computer equipment (100,000 kWh per year or 11%), with other uses consuming lesser amounts. The largest consumers of electricity among lab equipment were the large drying oven, mass spectrometer, CHN analyzer, smaller drying ovens and refrigeration units.

This study (Easter 2002) also reported that NREL used 595,000 gallons of water on average between 1995 and 2000. This is significantly more than AL's average use of about 392,000 gallons. Easter (2002) did not estimate nitrogen fluxes and did not compare NREL emissions to any local or natural reference basis. The NREL report suggested several measures for reducing environmental impacts, including choosing renewable wind sources for its electricity, installation of motion detectors to reduce lighting needs, reducing travel by use of teleconferencing technologies, purchase of recycled paper, replacing cathode ray tube (CRT) computer monitors with liquid crystal display (LCD) monitors, shutting down computers at night and other measures.

Comparison of the present study to ecological footprint analysis (Wackernagel et al. 1999, RP 2006) is also informative. The results in Tables 1 and 2 provide a general way to compare the methods here to ecological footprint analysis. The estimates of "spatial use intensity" for C and N emissions and energy and water uses for AL are conceptually similar to footprints – both are estimates of natural capacity on a per area basis as the reference for gauging the sustainability of human activities. One major difference is that ecological footprints are based on estimates of biocapacity that are global – per acre capacities are averaged taking into consideration the relative productive and assimilative capacities and different total areas of forest, agriculture, developed and other land cover types worldwide (RP 2006). Another important difference is that ecological footprint analysis combines various environmental services or fluxes into a single estimate of biocapacity. That is, no separate accounting or analysis for C, N, energy or water is made. Instead, sub-totals of environmental impacts incorporating all these currencies are made for energy, housing, food, goods and services and transportation. One important benefit of ecological footprint analysis is the potential for standardization of such auditing practices and the ability to compare between regions and organizations. As is often the case, larger scale generalization must come with a trade-off of smaller scale detail and precision. There may be times when more specific auditing measures like those employed here are worth the loss of global comparability, such as for comparisons within the Chesapeake Bay region.

Extensions and Implications for Strategic Action

Considering the ways in which AL's energy use changes seasonally, it may be fruitful to consider the general practice of altering a large indoor environment in ways that are "out of phase" with the local outdoor environment (see Figure 3.5). That is, can we consider that heating a large building in winter and cooling it in summer may be generally unsustainable and likely to lead to environmental problems? For an alternative approach, forests and forest dwellers of the local area may provide informative examples. Deciduous trees, perennial herbs and certain mammals such as bears and groundhogs alter their activity patterns to be more in phase with seasonal cycles by decreasing energy needs and production in winter, switching into dormant or underground phases or hibernating. Such adaptations enable these plants and animals to avoid the energetically costly indoor heating and cooling practices of AL and most humans in the developed world. While specific examples of harnessing such natural role models are not ready available, the emerging field of biomimicry (Benyus 2002) provides a possible methodology for development of real designs or technologies.

An important but likely controversial implication of this study is to question the view that a lack of environmental education in general plays a large role in current human-environment problems. The results suggest the need for a better examination and definition of what specific kinds of environmental education can lead to sustainable operations and real problem solving. If those in environmental science – clearly those most educated in the fundamental workings of environmental processes and humanity's dependence on essential ecosystem services - are actively participating in causes of major environmental problems, then a lack of education does not seem a general cause of such problems.

Some other factors appear to be of greater importance. It is as if forces operating in the larger socioeconomic system – perhaps a shared belief that technological advances will make it easy for others to clean up the mess we make, or competition amongst peers for discovery, prestige and funding - influence environmental science workers and their organizations to act against their own better judgment. Or perhaps something in the larger cultural worldview is considered to be of even greater importance. Perhaps a priority of providing *financially* for children and for retirement is considered more important than providing *environmentally* for progeny. These are speculations, but the need for similar explorations into other ultimate, systemic causes of environmental degradation appears real.

Considering the question posed at the start – whether environmental science can help society achieve sustainable ends via unsustainable means – the present study suggests the importance of the integration of means and ends. Given that we know real and specific details of the unsustainable and problematic nature of the C and N emissions and energy use associated with AL's operations, and have no evidence of any possibility of substitutes or innovations able to make the C, N and energy imbalances moot, it seems that the unification of long-term ends and short-term means is warranted. This view is tantamount to treating environmental sustainability as a journey or process as well as a destination or product. And it implies the need for continual attention to the *environmental quality of the science process* as equal consideration with traditional science quality criteria such as rigor, completeness, replication, parsimony and testing.

Given the current world environmental crisis, scientific and environmental quality may now intersect. One aspect of the intended and hoped for novel insight from this self-examination study is that we may see that the same issues, challenges, strategies and organizing principles that we in environmental science and ecology have studied and learned to be fundamental in communities in the natural world apply fully to ourselves as well. In this sense the reflexive application of fundamental principles of environmental science and ecology to the real operations of these sciences themselves is another rigorous test of the validity of these principles.

Would it be better or worse for environmental science to become sustainable, to internalize its environmental impacts? In the sense of leading by example as a strategy to solve environmental problems, it clearly would be better. The strongest proponent of this strategy may have been Albert Schweitzer, who said, “Example is not the main thing in influencing others. It is the only thing.” (Bartleby 2006). The fact that very few individuals or organizations provide examples of sustainable practices, combined with the ongoing difficulties we have in solving our environmental problems, suggests the links between example, influence, change and outcome may be critical at this time. The main downside seems to come from considering competition for funding and resources among other sectors of society. Those considering unilateral, pro-active reductions of environmental impact may fear being at a disadvantage relative to peers and adversaries who do not likewise begin to reduce. An ideal middle ground might be for environmental science to commit to reduction of energy use and associated impacts at the same time as, and in cooperation with, one or more allied sectors (e.g., local and/or state government, science funding agencies, sustainable agriculture or environmental businesses). In this way the “pain of converting” or the potential disadvantage to moving toward environmental sustainability would be lessened and the overall environmental benefits increased.

Another positive interpretation of these results is the potential to study and solve difficult environmental problems very close to home – in our own labs and on our own campuses. A leader in sustainability at Oberlin College, David Orr (1992) wrote:

> Ecological education will, first, require the reintegration of experience into education, because experience is an indispensable ingredient of good thinking. One way to do this is to use the campus as a laboratory for the study of food, energy, materials, water, and waste flows. Research on the ecological impacts of a specific institution reduces the abstractness of complex issues to manageable dimensions, and it does so on a scale that lends itself to finding solutions, which is an antidote to the despair felt by students when they understand problems but are powerless to effect change.

Further, if we in environmental science can solve excess nitrogen and the intertwined energy, carbon and water problems in-house, the spreading of success stories and functional solutions to other sectors of society ought to be much easier in comparison. Another hopeful potential is that a concerted program to reduce energy and materials use in environmental science could lead to *better science*. One way this could happen is that the impetus of tailoring the operations of science to be compatible with the physical supplies and capacities of the local environment could spur new discoveries as each science lab strives to become more keenly and intimately aware of its local environment.

Additional qualitative, quantitative and comparative self-examination of environmental science may confirm that the root cause of the general human-environment problem, or excess N loading in specific, is not primarily "out there", as in a cause existing somewhere separate from humans and our individual and collective minds or intelligences. The reported research suggests that we in environmental and ecological science may have to look no farther than ourselves to see and experience both the ultimate effects of these problems and the root causes. Similarly, this line of thought suggests that solutions are not likely to come primarily from "out there", as in 1) discovery of new objective knowledge of the external world, 2) substitution of new energy or materials resources, or 3) technological devices or increases in efficiency of existing devices and machines. Instead, the route to lasting and effective solution may be one that leads inward, and the novelty, innovation and new creations that are needed may be new constructs within the mind or changes in heart or spirit, other key inner human realities. If we are to act like and achieve the elegant and excellent N retention and C sequestration capacities and other environmental successes of living communities such as forests (Fiscus 2007a) we may first have to learn to "think like an ecosystem" (Tippett 2004). Such a collective intelligence (Wolpert and Tumer 2000) as a healthy social mental or knowledge capacity (i.e., wise and effective science) may be required for collective health of a "social body" as integrated in mutually enhancing relationship with the necessary environmental services such as those providing and processing C, N, energy and water.

Summary and Synthesis

One counter-argument to the conclusion that AL and environmental science are unsustainable and are participating in causing major chronic-systemic environmental problems is that the products of publications, trained graduate students and consulting services could lead to improvements that more than compensate for the short-term excesses of use and emission they require. While this is generally possible, it does not seem likely. This argument would require that the 25 published articles and 5 graduating students per year result in more than 420,000 kg of CO_2 sequestration and 910 kg of reactive N uptake or denitrification. This C and N assimilation might be achieved via new technologies, better management practices or by increases in capacities by enhancement, preservation or restoration of natural areas. For energy, this argument would require that AL's annual products, graduates and services replace the equivalent of more than 14 million megajoules of renewable energy capacity in order for the operations of AL to generate a net gain in energy capacity for humanity in the long-term. If it became the intention and priority to offset environmental impacts, these estimates provide a basis for doing so via market based emissions trading, or by acquiring or restoring land such as forests and wetlands with these natural capacities. For example, if AL acquired or arranged to have set aside 141 ha (about 350 acres) of forested land per year, that land could effectively offset total annual C and N emissions.

Looking again at the two sub-systems of AL, one could say that humans are the bridge between science and technology on one hand and nature, environment and life on the other. Currently our machines, buildings, equipment and behaviors bring us great benefits but also cause serious environmental damage. We must be like mediators and find some way to resolve the conflict between these two realms. This process would necessitate explicit assessments of the environmental costs and science benefits of machines and equipment.

Balancing the objective and relational science challenges described in the introduction can present a third challenge of weighing the relative importance or strategic priority of objective versus relational orientations to environmental science. Which is more important – traditional science goals like discovery of new knowledge, or success on the new front of solving environmental problems? Is it more important to be *value neutral* (as in promoting objectivity, non-advocacy and independence), or *carbon neutral* (as in generating zero net CO_2 emissions)? Can science institutions and scientists as individuals be objective in the scientific sense if we are entangled in real material ways (C, N, energy and water fluxes) with major environmental problems? Or, rather than pitting such choices as either/or, must we value and do both? Such are the questions that arise when one accepts that environmental science itself is now "on the inside" of its main system of study. The study reported here seeks to turn these potentially difficult questions into advantages by using them to generate novel perspectives and insights via development of self-reflexive environmental science.

In essence this work asks of environmental science, *Can we really help others before we have our own environmental "house in order"? What would it take to get our own environmental house in order, to achieve environmental sustainability of our own operations? Would it perhaps be easier and more effective to develop and spread solutions to other sectors of society after we have first developed and tested functioning* *solutions and achieved success in our own environmental science institutions?* Some initial answers and discussion are provided here, but more dialogue and action are needed.

The central problem as framed here is akin to asking, *How do we sustain environmental science (as a subset) and human society (as a whole) in terms of fundamental energetic and biogeochemical relations?* And this question could potentially be generalized further. Related questions include: *How does any process, community or system sustain itself over the very long term? How can any process or system maintain or increase its productive capacity as it achieves production? How can any system increase its assets, potential, relative environmental standing or odds of survival in the future? How can any system improve itself, its environment and its relationship to the environment as it operates?* These questions in turn are not far removed from some of the most fundamental questions of all such as, *What is life?* (Shrödinger 1944).

Returning to the issue of values, we might ask whether even this is the ultimate level of cause for our current problems. Is the subordination of environmental values to socioeconomic and other values itself caused by some deeper cause? Perhaps at some deeper level it is fear - fear of death or fear of the environment – that operates to make it seem as if environmental degradation is necessary or acceptable. Or conversely, perhaps the way we take life support and environment services for granted comes from some deep belief in the capacity of the environment to heal from all disturbances and provide for our needs indefinitely. The general assumption of organisms, individuals and the human self as separate from the environment may also be implicated. The concept of the *intrinsic value* of nature and all life forms provides a possible link to an equalization of environmental and socioeconomic values (Wittbecker 2000). It may be helpful to acknowledge that we don’t have to “put ourselves down” or decrease our own forms of human value. Rather, we just need to raise others up, to promote the value of our fellow beings and environmental home - not to a level above ourselves, merely to an equal level of value.

Howard Odum is perhaps the most famous ecologist who advocated reduction of our energy and materials consumption. He and his wife wrote (Odum and Odum 2001):

> Instead of denial, it is time for people at all levels of society to plan for a better world in which we use less. There should be task forces throughout society working on descent.

Their vision of a “better world in which we use less” suggests that we need not consider such reduction, downturn and contraction as failure or retreat. Instead, it can be both normal given the environmental circumstances and healthier than continuing trends and patterns that lead to environmental degradation. Odum and Odum (2001) also describe a gift of being “enriched with knowledge developed in the fuel-rich century of complexity” as we change course and head back down toward the lower energy basis similar to sustainable communities like forests. In this sense the whole cycle of exponential growth, reaching and overshooting the limits of our environmental carrying capacity, sensing the problems and the conscious downturn has been a great experiment, and we in science may have an important role to play in gleaning the lessons from this great experiment. Collectively learning these lessons could find us all greatly enriched with knowledge about ourselves, our environment and the best forms of relationship and organization for long-term environmental and social quality.

In a last example of self-reflection and self-examination, the author must admit that these same methods find his own science practices as both unsustainable and part of the problem. Estimates for computer use (two personal computers running eight hours each work day) and commuting (car travel 22 miles roundtrip each work day) provide sufficient evidence of the imbalance of the author's own science research practices with respect to local C and N assimilation capacities and use of non-renewable energy without replacement. Following such environmental reckoning one must decide if he/she is willing to publish science articles or make recommendations for problem solving that in effect say, when one reads between the lines, "Do as I say and not as I do". Personal changes for the author such as biking to work, moving so that work and home are nearer, examining the use of machines, considering the impacts of each action and reducing energy use and environmental impacts are underway, albeit with slow progress. Additional and ongoing self-critical examination focuses on which aspects of environmental and ecological science are essential and which are affordable given the resources they require.

In the humbling moments of self-reflection inspired by the global ecological crisis it becomes apparent that there are limits to what we humans can do, limits even for our advanced scientific and technological capacities. Some things simply are not substitutable or replaceable, and we take them for granted at our own peril. No matter how crucial our personal or institutional mission, if we take the most basic necessities of life for granted we cannot assume that local excesses of emission or depletions of capacity will be taken care of elsewhere in time or space or by someone else. Years of scientific study of environmental and ecological processes provide a solid foundation for knowing that the processes associated with C, N, energy and water are fundamental and must be attended to explicitly and with margins of safety.

In perhaps the most concise and straightforward terms this research simply suggests the best environmental strategy is to give back equal or greater quality to the environment compared to the quality we take from the environment. Otherwise the environment, our relation to it, and we ourselves will all be degraded and compromised. Allenby (2005) proposes the following principle from Immanuel Kant as a global environmental ethic: “Act such that the world that would be expected to result if every entity acted in an equivalent manner would be an ethical and desirable expression of human design”. This principle builds on the Golden Rule, which Allenby (2005) states is common to most cultures, and it also acknowledges the strong human role in designing and shaping the world.

If we love our fields of environmental and ecological science enough to do whatever it takes to improve them; if we love ourselves, our children and our communities enough to do whatever it takes to solve our current chronic-system environmental problems; and if we love our natural forests, wetlands, estuaries and other systems of study enough to do whatever it takes to preserve, enhance and pass them on to the next generation in health and vitality; then we must transcend our current cultural context of over-consumption. Luckily the systems we study - the forests and other living communities – have been teaching us ways to do this, practical ways of living sustainably in any environment, all along.

Chapter 4

Comparative Network Analysis Toward Characterization of the Necessary and Sufficient Organizational Criteria for Environmental Sustainability

Introduction

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 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. Comparing human ecosystems to 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 and what specific changes could improve our environmental relations and help solve problems. Comparative ecosystems studies may also reveal time-tested, proven successful and robust organizing principles in ecosystems that we can use as role models via a form of "technology transfer" like that developed in the fields of biomimicry (Benyus 2002), permaculture (Mollison 1996) and ecological engineering (Kangas 2004).

The research project described here sought to provide fundamental information about quantitative, physical aspects (i.e., biophysical carrying capacity) as well as qualitative, relational aspects (i.e., organizational form and dynamic behavior) of environmentally sustainable human-environment systems. Herman Daly (1990) introduced the clearest and most concise principles for sustainability. His “input-output rules” for sustainability require use of resources at rates less than natural environmental generation rates and also address waste assimilation capacities and non-renewable resource use (for the full text of the rules, see Chapter 1 in this dissertation). One goal of this study was to examine whether internal ecosystem and network configuration patterns could be developed and correlated with these fundamental boundary flux and input-output principles. One question addressed was, are unique network structural patterns associated with, and key to actualizing, ecosystems able to meet the Daly input-output rules? And do network structural patterns differentiate between those systems that are environmentally sustainable and those that are not?

Based on prior study of ecological network analysis (ENA), the hypothesis 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-system network organizational properties – the number of network roles (limited range of 2 to 4.5) and the effective connectance per node (limited range of 1 to 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 window of vitality was tested for its ability to help define sustainability via comparative network analysis. This test involved treating natural ecosystems as environmentally sustainable reference cases based on 1) general adherence to the Daly

(1990) input-output rules above and 2) observations and historical evidence that forests and other natural ecosystems self-perpetuate and continue to improve (e.g., build and enhance soils) over time scales of 10,000 years (Baisden and Amundson 2003), very long relative to time frames of human cultures.

The second major hypothesis tested relates to an industrial ecosystem typology developed by Allenby and Richards (1994). These two industrial ecologists presented a simple classification scheme characterizing fundamental system differences along a continuum from heavily industrial and resource-dependent ecosystems (Type I) to ideal and resource self-sufficient ecosystems (Type III). Their three ecosystem organizational types are categorized in ways compatible with the Daly rules via similar focus on system input and output boundary fluxes. The three ecosystem types vary in degree of reliance on non-renewable versus renewable resources. Their ecosystem types also include general reference to internal organizational structure, mainly in the form of varying degrees of material cycling. The comparative ecological network analyses reported below examined the utility of this typology and its applicability to both a human food web network and four non-human ecosystem networks. I predicted that the human network would be best classified as a Type I industrial ecosystem and that natural ecosystems would be similar to the more sustainable ecosystem Type III.

The specific human food web studied was a small sub-network within the total 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. While a very limited and single case, the U.S. beef supply network possesses several key properties that should allow many results to be generally applicable to the industrial food system. Based on initial findings, 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 as a whole was deemed representative of many 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 issues characteristic of major environmental problems and efforts to define and achieve environmental sustainability.

In addition to tests of two specific hypotheses regarding network and ecosystem organization relevant to sustainability, this research project involved exploration for additional comparative network analysis measures and methods useful for such efforts. Several surprises were encountered, and 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, chronic and systemic human-environment problem.

Data and Methods

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 (e.g., 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 understandable via focus on parts of the network in isolation. Ulanowicz (1999) elaborates this view in his “ecological metaphysic” and promises improvement for mainstream life sciences now based on mechanistic and Darwinian philosophical foundations (Ulanowicz in preparation). This theory has powerful implications for ecological science in that it entails that ecology is a fundamental or basic science in its own right and thus not a discipline derivative of or reducible to others like biology or physics.

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 energy or material that is exchanged in a network. A dataset for ENA is constructed by identifying who eats whom and by how much. Compared to dynamic modeling, the network approach is 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.

In ENA research, in addition to data for internal stocks and transfers between network compartments two types of exports are also distinguished and quantified (Ulanowicz 2004). Transfers of useful medium with potential food or nutrient value for another species or entity outside the focal network are called exports. Transfers of non-usable medium, such as energy completed degraded to heat or nitrogen reduced to its lowest redox state in N_2, are treated as terminal transfers or respirations.

Comparative Network Analysis

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. The focal nutrient examined in the human case was nitrogen (N), as it is currently the focus of extensive and intensive research as associated with excess N loading to the Chesapeake Bay and the subsequent problems this causes.

Comparative network analysis was the basis for testing the hypothesis that human food web networks are organized in ways that put them outside the “window of vitality” (Ulanowicz 2002a, Zorach and Ulanowicz 2003). Network methods were also employed to test the hypothesis that human ecosystems are most like Type I industrial ecosystems of Allenby and Richards (1994) while natural ecosystems are most like their Type III ecosystems. Finally, a suite of network analysis measures and indices were explored for additional insights into how human and natural ecosystems are organized and how this knowledge can be used to inform sustainability science and action for sustainability.

Human Diet in the U.S.

To construct a food web network for humans in the U.S., data analysis was done to identify the major food items in typical U.S. diets and quantify the contributions of each item to human ingestion of energy and nitrogen. I used two USDA nutrition datasets

(USDA 1998**,** USDA 2006) to construct a list of the top food items by average daily mass ingested. These foods accounted for 94% of total daily calories using an estimated average of 2,002 calories per person per day in the U.S. (USDA 1999). Ingestion data came from the USDA SR14 (Standard Reference 14) survey of food intakes over 2 days by 14,262 individuals between 1994 and 1996 (USDA 1998). The numbers reported were mean quantities of each food item eaten per person per day. The dataset is broken down by ages and gender, and I used summary data for both genders and all ages 2 and older. To convert the food items and quantities into energy and protein amounts, a second USDA SR19 dataset was used (USDA 2006). This reports water, fat, energy, protein, carbohydrate and other nutrient contents, and a specific N and protein conversion factor for each food item was provided in the "N_Factor" field in the SR19 Food Description file. The documentation reports that the general factor of 6.25 is used to calculate protein in items that do not have a specific factor. The inverse of this factor is equivalent to 16% N in protein.

The 63 leading food items by mass ingested are listed in Table 4.1 as ranked by protein amounts, as protein is the major source of nitrogen ingestion. The nutrient contents (e.g., water, energy, protein, fat) of many of these items are category averages of more specific actual items. For example, ground beef averages over 25 varieties of ground beef with differing percentages lean and fat and different cooking methods. The milk category averages over 23 varieties of fluid, whole, reduced fat and non-fat milks.

From this data ground beef was ranked the top source of protein in 1994-1996. The original intention was to construct networks for other major protein food items such as milk, chicken, beans and turkey, as well as fat sources like vegetable oil and

Table 4.1. Average daily intake amounts, nutrient contents, protein and nitrogen of major food items in U.S. diet, 1994-1996. (USDA 1998, 2006).

Food item	Daily Intake (g)	% Water	% Fat	% Ash	% Carb	Energy (Kcal/100g)	% Protein	Protein (g)	N factor	Protein % N	Daily N Intake (g)
ground beef	25	59.1	14.2	1.0	0.0	238.0	25.7	6.43	6.25	0.16	1.03
fluid milk	182	90.1	0.9	0.9	4.8	40.0	3.3	6.02	6.38	0.16	0.94
chicken	21	60.2	11.7	1.1	1.7	221.7	25.9	5.44	6.25	0.16	0.87
beans and peas	17	11.4	1.2	3.7	61.6	338.1	22.2	3.78	6.25	0.16	0.60
turkey	14	64.0	8.3	1.4	1.2	186.5	25.3	3.54	6.25	0.16	0.57
cheese (solid)	13	43.4	24.2	4.4	4.3	331.0	23.8	3.09	6.38	0.16	0.48
lowfat milk	88	89.9	1.0	0.8	5.0	42.0	3.4	2.97	6.38	0.16	0.46
beef steaks	10	58.5	11.8	1.2	0.0	228.6	28.7	2.87	6.25	0.16	0.46
luncheon meats	19	59.1	20.7	2.7	3.7	257.3	13.3	2.52	6.25	0.16	0.40
fish (finfish)	10	66.7	6.3	2.0	0.0	161.4	24.9	2.49	6.25	0.16	0.40
spaghetti	41	62.1	0.9	0.3	30.9	158.0	5.8	2.38	5.70	0.18	0.42
pizza	19	43.4	12.4	2.6	29.5	278.0	12.2	2.32	NR		
eggs	19	73.7	12.0	1.1	1.1	163.4	12.1	2.30	6.25	0.16	0.37
dinner rolls	20	28.4	6.5	2.2	52.0	310.0	10.9	2.17	5.80	0.17	0.37
white bread	26	36.4	3.3	2.0	50.6	266.0	7.6	1.99	6.25	0.16	0.32
whole milk	57	88.3	3.3	0.7	4.5	60.0	3.2	1.84	6.38	0.16	0.29
cereal (ready to eat)	16	3.4	4.0	2.8	81.6	377.3	8.1	1.30	6.25	0.16	0.21
soups	52	89.4	1.5	1.2	5.6	44.8	2.3	1.21	NR		
wheat bread	11	35.7	3.6	2.2	47.5	266.0	10.9	1.20	5.80	0.17	0.21
nonfat milk	34	90.8	0.1	0.8	5.0	34.0	3.4	1.15	6.38	0.16	0.18
peanut butter	4	1.4	48.4	3.2	22.0	586.4	25.0	1.00	5.46	0.18	0.18
chips and popcorn	10	2.0	23.7	3.0	62.9	485.9	8.3	0.83	NR		
rice	31	70.2	0.4	0.3	26.6	123.1	2.5	0.78	5.95	0.17	0.13
icecream	15	62.4	7.0	0.9	25.5	174.2	4.1	0.62			
potatoes	20	71.4	3.3	1.4	21.2	122.4	2.6	0.52			
oranges	53	86.8	0.1	0.4	11.8	47.0	0.9	0.50			
orange juice	55	88.4	0.3	0.5	10.1	44.0	0.8	0.44			
french fries	13	61.5	5.2	1.9	28.7	172.0	2.7	0.35			
cooked cereal	16	82.2	0.7	0.6	14.5	71.2	2.0	0.32			
mashed potatoes w/ butter, milk	15	75.6	4.2	1.5	16.8	113.0	1.9	0.28			

Table 4.1, continued.

Food item	Daily Intake (g)	% Water	% Fat	% Ash	% Carb	Energy (Kcal/100g)	% Protein	Protein (g)	N factor	Protein % N	Daily N Intake (g)
coffee	224	99.4	0.0	0.4	0.0	1.0	0.1	0.27			
corn	10	75.8	0.7	0.8	20.1	84.1	2.7	0.27			
oat cereals	10	85.3	1.0	0.3	10.8	63.0	2.6	0.26			
candies and chocolate	4	3.7	24.7	1.3	63.5	484.8	6.2	0.25			
beer	78	94.2	0.0	0.1	1.9	33.2	0.3	0.22			
lettuce	16	95.1	0.2	0.6	2.8	15.0	1.4	0.22			
bananas	16	74.9	0.3	0.8	22.8	89.0	1.1	0.17			
tomato sauce	13	89.1	0.2	2.0	7.4	37.0	1.3	0.17			
fluid cream	6	72.3	20.0	0.6	4.5	204.2	2.5	0.15			
fruit drinks	87	87.8	0.1	0.2	11.8	47.0	0.2	0.14			
carbonated drinks with caffeine	193	90.3	0.0	0.0	9.6	37.0	0.1	0.14			
onions	12	91.0	0.1	0.6	7.2	31.4	1.1	0.13			
tomatoes	12	94.5	0.2	0.5	3.9	18.0	0.9	0.11			
candy	2	5.7	14.0	1.0	74.6	433.0	4.3	0.09			
grapes	12	80.5	0.2	0.5	18.1	69.0	0.7	0.09			
salad dressing	5	58.2	24.2	2.7	13.5	271.0	1.2	0.06			
mayonnaise	5	51.0	34.2	1.9	11.9	352.9	1.0	0.05			
applesauce	21	79.6	0.2	0.1	19.9	76.0	0.2	0.04			
margarine	6	35.3	61.1	1.8	1.1	547.9	0.6	0.04			
apples	14	85.6	0.2	0.2	13.8	52.0	0.3	0.04			
tea	123	96.7	0.0	0.1	3.2	12.8	0.0	0.03			
carbonated drinks (diet, no caff.)	26	99.7	0.0	0.0	0.2	1.0	0.1	0.03			
coffee decaf.	31	99.3	0.0	0.1	0.0	0.0	0.1	0.03			
syrup	3	30.0	0.1	0.5	68.8	256.5	0.5	0.01			
apple juice	17	87.9	0.1	0.2	11.7	47.0	0.1	0.01			
wine	9	85.7	0.0	0.3	3.8	86.7	0.1	0.01			
jams and jellies	2	40.5	0.1	0.2	58.9	216.6	0.4	0.01			
sugars granulated	44	0.0	0.0	0.0	100.0	387.0	0.0	0.00			
vegetable oil	18	0.0	100.0	0.0	0.0	877.4	0.0	0.00			
carbonated drinks (no caff.)	60	89.6	0.0	0.1	10.6	41.0	0.0	0.00			
carbonated drinks (diet)	54	99.8	0.0	0.1	0.1	0.0	0.0	0.00			

carbohydrate sources like sugar. But the beef supply network was so complicated that it became the sole focus of the project. The complexity of the full U.S. human food web seems several orders of magnitude greater than that of even the most detailed natural food webs such as Chesapeake Bay and Florida Everglades. While this does raise questions about the validity of comparisons, it is hoped that a comparison of the beef supply sub-network to analogous sub-networks such as the trophic pyramid below alligators and bluefish will provide meaningful results. Also, metrics and techniques of ecological network analysis are general and robust and have been used for comparisons of different networks.

Construction of the Human-beef Supply Network

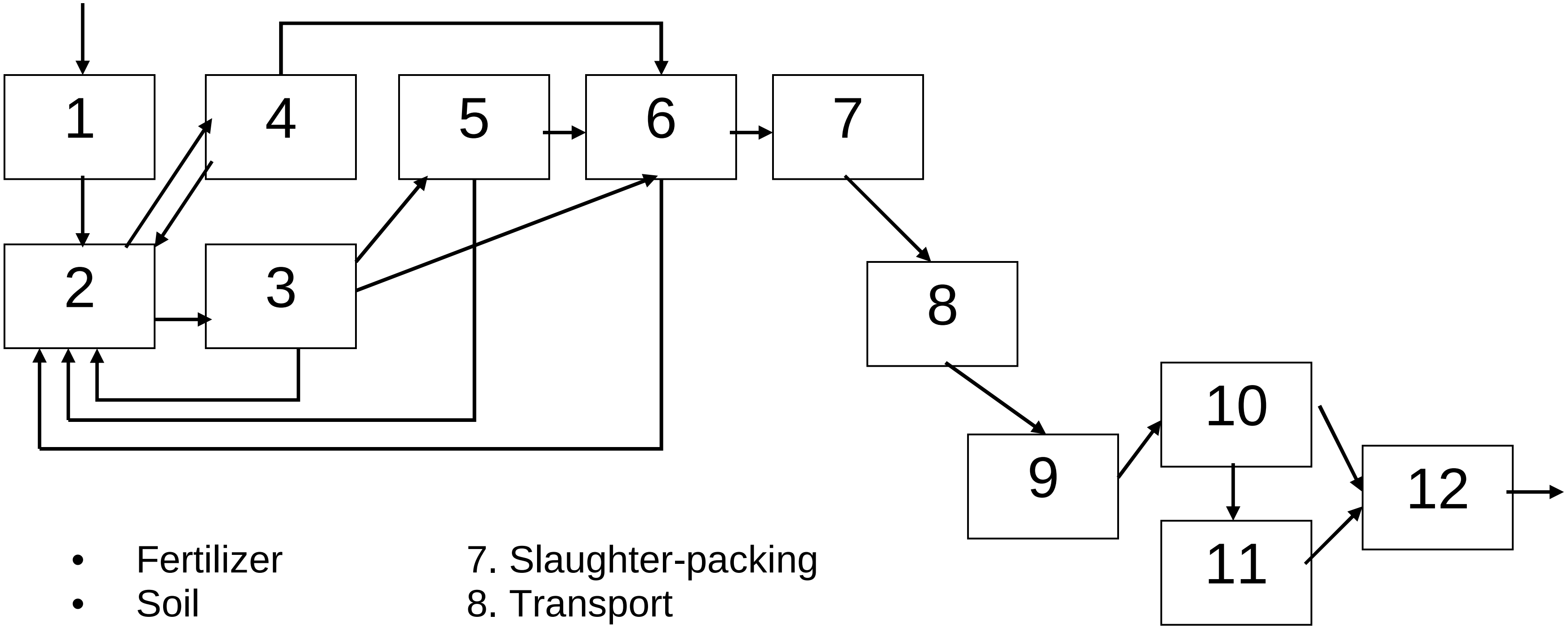
Boundary, Scale and Component Assumptions

The focus for data collection was a general and simplified representation of nitrogen (N) flux in the beef supply network for Allegany County, Maryland. The system size was based on the 2005 population of approximately 75,000 people. An annual time step was used for network fluxes, and national beef and agricultural production data for 2005 were used when possible. The focal component in the network was the beef N input to humans. The network was traced forward to a final compartment in wastewater treatment, and traced back to nitrogen fertilizer production as the primary N input to agriculture. The other components considered were soils, grass and hay production, feed corn production, cow-calf operations, cattle feedlot operations, slaughter and meatpacking, transportation, retail (supermarkets), and home refrigeration and cooking. These compartments and the flow links between are shown in Figure 4.1.

The rationale for the compartments chosen and for comparing them to ecological organisms, species or compartments is based on several key assumptions. Like natural ecological network participants, each of the human-beef supply compartments take in a food item (beef), 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 natural food webs, each compartment also uses energy and causes fluxes of N and C in the transformation process it performs, analogous to metabolism, albeit a generalized “industrial metabolism”. Finally, the compartments defined and quantified are associated with real corporate entities. Corporations form an economic boundary similar that also enables tracking of energy and material fluxes via data reported, government statistics and similar information sources. One problem with this extension of ecological network analysis to the U.S. human food system is that beef (and other foods) is not actually ingested in industrial compartments and it is not transformed into another life form via true metabolism. This real difference will be kept in mind during comparisons and bears future work to examine its validity and consider alternative approaches.

Figure 4.1 (next page). Diagram of humans-beef nitrogen network.

U.S. beef supply chain
Human food web nitrogen sub-network



- Fertilizer
- Soil
- Grass-hay
- Corn
- Cow-calf
- Feedlot

7. Slaughter-packing
8. Transport
9. Retail
10. Home refrig. & cook
11. Humans
12. Waste treatment

Figure 4.1

While these compartments are specific to the beef supply chain, the general network structure seems applicable to many other major food items. If the cow-calf and feedlot stages were generalized to one or more “agricultural production” components and the slaughter and meatpacking stage generalized to one or more “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.

I assumed the average Allegany County citizen has the same annual beef consumption as the average U.S. citizen. An estimate was obtained for per capita production of beef measured as weight of dressed carcasses (butchered and ready for sale) from slaughter and meat packing operations. Total U.S. production (dressed carcasses) in 2005 was 24.8 billion lbs (National Agricultural Statistics Service (NASS) 2006). The net balance of imports and exports would have added a bit to this total supply, but these numbers were not considered. Based on U.S. population in 2005 of 296,410,404 (U.S. Census Bureau 2006), this gave an estimate of 38 kg (83.7 lbs) annual beef production per person in the U.S.

Gregory et al. (1994**)** estimated losses from dressed carcasses (average weight 333 kg) to retail sales (average weight 225kg) as 32%, giving an estimate of 25.8 kg (56.9 lbs) per person purchased at retail and transported home. An estimate of loss at home due to cooking waste, spoilage, uneaten portions and other causes was set at 10% based on Smil (2002), which yielded an estimate of 23.2 kg (51.2 lbs) per person ingested annually. This was checked for plausibility by converting the figure to an estimated 16 ounces of beef eaten per person per week, or 2.2 ounces per person per day. The estimate of 23.2 kg per person ingested was quite a bit higher than another estimate of 12.8 kg per year obtained from analysis of USDA food survey data (USDA 1998; see Table 4.1). This lower estimate only accounted for consumption of ground beef and steaks and thus did not include beef in other types of foods such as soups, luncheon meats, sauces and pizza. The lower estimate was also from 1994-1996 and beef consumption may have increased since then.

Using another national statistic of total production in weight of live animals gave an estimate of the average weight of live animal mass consumed per person. NASS (2006) reported 40.7 billion lbs total live production for 2005 giving an estimate of 137 lbs per person. Based on population, and using the average weight at slaughter of 570 kg (NASS 2006), this yielded an estimate of 8200 head of cattle to supply Allegany County’s needs for beef. These per capita and total beef consumption estimates provided the starting point for construction of the rest of beef supply network.

Working Upstream in the Beef Supply Chain

Starting with the human biomass (population) and annual beef N ingestion needs, I worked back to estimate all stocks, inputs and outputs needed to satisfy that human ingestion. At the end I traced the excretion of N in sewage to and through the wastewater treatment stage and estimated N fluxes associated with human mortality.

Data gathering for each compartment (e.g., retail) started with the known amount needed to supply the receiving compartment (ex. home refrigeration and cooking). Next I used scientific literature, online reports and government statistics to estimate losses, standing stocks and production inputs needed to supply the required output. This process was then repeated for all compartments. Whenever possible I considered multiple estimates for each stock, flux or conversion parameter. Most of these values and their sources are reported in Appendix A.

For some compartments such as soils, cow-calf operations and humans, it was important to consider how much production is needed to replenish productive capacity and sustain the compartment itself. These factors led to examination of flow loops inside some compartments and required iterative calculations to approximate balanced steady state conditions. In this process it was important to note if literature values of estimated losses were reported as percentage of standing stock, sales, or production output as these would result in different loss fluxes. Losses were at times reported in terms of whole animals (e.g., head of cattle lost to mortality) and other times as partial amounts of animals (e.g., percentage of total carcass lost as entrails, hide, bone and other unused portions of slaughtered animals).

The dataset construction process was very similar to standard methods of ecological network analysis such as those developed and reported by Ulanowicz (2002b, 2004). That is, the general approach is to quantify who eats whom and by how much. However, several important differences were encountered in this attempt to extend ecological network analyses to U.S. human and industrial food webs. One of these major differences is described next.

Steady State Assumptions

Ecological network analysis requires an assumption of steady state conditions for the ecosystem being studied. 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, it is assumed that 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. The standing stocks that enable production also 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, living human workers and a variety of other building and infrastructure aspects. Examples of types of productive capacity or standing stocks that enable production in the slaughter and meatpacking compartment, some of which contain or utilize N, 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. Instead, much of the industrial capacity for production is external to the local site of production and, most importantly, this capacity is *liquidated* or used without replenishment during production. Key forms of capacity like fossil fuels, soil organic matter and biodiversity are exploited to drive production with no allocation of any gains from production for their replacement. At the corporate level productive capacity is replaced by use of money (exchange value gained from sales of beef) traded for new, replacement or improved capital equipment and infrastructure. But 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).

Said another way, the mass and N of beef in the example slaughter and meatpacking unit does not cycle internally and is not internally transformed to regenerate other necessary elements of production. The partial exception is for the human workers. If human workers were included in each of the compartments, some of the N flow and beef production output could be allocated to reproduce and sustain the productive capacity (the humans themselves via their dietary intake of N in beef). For example, a staff of 100 workers would ingest about 100 kg N per year in beef. But since this flux is relatively small, and is indirect in that it is mediated by the economic system (workers earn wages as employees of slaughter and meatpacking plants and then exchange some of those wages for beef at retail outlets), it was not examined for this study. Even though a small and indirect flux, this does constitute a flow loop and form of network complexity that is worth further study.

Without fully resolving these issues, this project served to identify and begin to characterize them. The N fluxes for human workers 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 the discussion section). 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.

Standing Stocks and Biomass Estimates

I used a process of estimating reasonable residence times within each compartment to estimate standing stocks. Most industrial stocks are always moving through compartments in linear assembly line fashion. For example, I assumed that meat stays in a retail store about one day. Combined with an estimate of 1078 lbs of continual stock of meat in each of 11 stores/restaurants this scaled up to 234 kg N standing stock and matched the needed output from the retail units. The same process for the slaughter and meatpacking compartment using a rough residence time of 4 hours leads to a standing stock of 43 kg N, roughly the N in four head of cattle. It is interesting to note that beef (in the form of live animals) spends about six 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.

Details of how additional stocks and fluxes of N in beef were estimated for each compartment are described below.

Human Consumption and Ingestion

Using the value of 23.2 kg beef ingestion as above, values for protein content of beef and N content of protein were used to estimate annual human N ingestion from beef. The USDA (2006) nutrient data reported that ground beef is 25.7 % protein and steaks are 28.7% protein. These two values were averaged to give an estimate of 27.2% protein in beef. The same reference also used a conversion factor for protein as 16% N. This value was comparable to 17% reported by Sterner and Elser (2002) and a bit higher than the 10-14% reported by Bahar et al. (2005). Using these figures an estimated intake of 1.01 kg N per year or 2.8 g N per day from beef was obtained. This value is reasonable, but perhaps a bit high, as compared to an estimate of 12 g N ingested and excreted per person per day (Fiscus 2007b in preparation), assuming that much additional protein and N comes from other forms of meat (e.g., chicken, turkey, pork, fish), milk, cheese, beans and grains, eggs and other sources. The figure amounts to beef providing 23% of the total N intake. Scaling this up for Allegany County as a whole yielded 75,871 kg N from beef ingested per year.

Other data indicated that human bodies contain about 2.5% N on wet weight, live biomass basis. Several estimates found vary only slightly with Sterner and Elser (2002) reporting stoichiometric ratios that yield 2.4% N and 1925 data from Alfred Lotka of 2.5% N. Data from Lane and Schoeller (2000) result in 2.6% N. For an average person of 150 lbs or 68 kg, this amounts to 1.7 kg of N stored in the human body. Using the estimate of 12 g per day of total N (all sources) ingested and passing through the body gives a residence time of 142 days. That is, the average atom of N stays in the body for 142 days before being replaced by a new atom of N.

Home Refrigeration and Cooking

The compartment for home refrigeration and cooking was included as an important unit based on the significant energy and nitrogen fluxes associated with this integral aspect of U.S. lifestyle. Heller and Keoleian (2000) reported that 32% of the total energy of the U.S. food system is used in household storage and preparation. Millstone and Lang (2003) also estimate that in 2000 half of money spent on food was for eating away from home at restaurants and similar operations. USDA statistics (2006b) for 2005 put food expenditures away from home as 46.5% ($453.3 billion dollars away from home compared to $973.6 billion total food expenditures, excluding alcohol). Refrigeration, cooking and associated N fluxes for such non-home enterprises were treated as combined into the home compartment.

While worth examination as a unit in the beef supply network, the N fluxes associated with NOx emissions due to home energy use was not included in this analysis.

A very rough ballpark estimate was done for N fluxes associated with home refrigeration and cooking for Allegany County using 1) the county's proportion of the total U.S. population (0.025%), 2) an estimate of N emissions per unit of energy consumed in a university research building (6.8 x 10^{-8} kg N/Btu, Fiscus 2007b in preparation), 3) energy used in household storage and preparation in 1997 (3.25 x 10^{15} Btu, Heller and Keoleian 2000) and 4) an estimate of beef as associated with 10% of the total home refrigeration and cooking needs. The resulting value of 5,527 kg of N per year is small relative to how much N in beef is moving through all homes in Allegany County, but it would be more complete to include this in future studies.

Using the same estimate of 10% loss of beef total mass at home or restaurant as above, the amount of N flux from retail into the home was set at 84,301 kg. Of this 10% loss, half was assumed discarded as solid waste into a landfill and half discarded down the drain into the sewer system. This loss was assigned as two output fluxes from the home cooking compartment - one a respiration or terminal flux to a landfill, the other a flux of useful or biologically active material with N to the wastewater treatment compartment that would join the N flux from human sewage wastes.

At this point in the network, beef is 4.35% N on a wet weight basis – the product of the proportion of N in protein (16%) times protein in beef (27.2%). Beef as eaten is about 59% water (USDA 2006a).

Retail

To estimate the beef and N flux into the retail compartment, I again used an estimate of 32% loss from dressed carcass to retail weight as above (Gregory et al. 1994). This loss in mass was considered to be fat and bones removed in butchering of dressed carcasses. As such this processing step was treated as resulting in an increase in the proportional N content in the beef, since bones and fat contain less N than protein and muscle. For example, Sterner and Elser (2002) stated that phospholipids are 1.6% N and glycerols, fatty acids and waxes contain no N at all. They also say that bone is about 4% N and blood about 3.5% N. Skin, however, is very high in N at 16%.

The N content in beef at this stage was estimated as 3% total mass, wet weight basis as an intermediate value between 4.35% of retail meat and 1.6% N reported for live growth weight gain for feedlot cattle (Hao et al. 2005). These calculations result in an N content of 0.4% for the 32% of dressed carcass mass that is discarded in producing retail cuts of beef. This N content figure may be low and would benefit from additional scrutiny of data on differential N content between dressed carcass, discarded portions and retail beef.

Transportation

The transportation compartment represents trucking from slaughter and meat-packing plants to retail outlets. I did not gather data on energy use and associated N fluxes for this step, but added a nominal 1% terminal loss as likely associated with spoilage due to rare events like breakdowns. To estimate stock I assumed a 2-day transit and residence time in this compartment to represent trucking from the mid-west to

Allegany County. Transportation also occurs many other times in the beef supply chain, for example from cow-calf operations to feedlots (Pollan 2006) as well as from retail to home. Inclusion of just the one transportation compartment is thus a minimal treatment of this function and under-estimates its importance overall.

Slaughter and Meatpacking

Slaughter of beef cattle and meatpacking has become increasingly automated and industrialized over many decades. MacLachlan (2001) and Horowitz (2006) document many of the incredible details of this historical development. This story includes the invention of an automated restraining, stunning and killing conveyor system able to decrease the time and human labor for this process while also preventing damage to the beef product that can be caused by physiological chemicals released if animals sense fear, are stressed and experience trauma (MacLachlan 2001). The slaughter process is likely the most labor-intensive stage in the beef supply chain and many other steps have not been amenable to automation due to variable sizes and weights of the animals. As a result much of the strenuous human labor required in butchering has led to repetitive motion and trauma disorders by workers, high employee turnover rates and insurance costs, high labor costs and very slim margins for the meatpacking industry (MacLachlan 2001). Perhaps related to these pressures, the meatpacking stage is also the one most consolidated economically and just five major corporations - Tyson, Con Agra Beef Co., Cargill, Farmland National, and Beef Packing Co. - control 81% of the slaughter and meatpacking market in the U.S. (Millstone and Lang 2003). Salin (2001) reported 64 packer operations in total in 2000 with the 4 largest then controlling 82% of production.

NASS (2006) reported that 0.55 percent of beef cattle slaughtered were condemned and discarded due to unacceptable meat quality. Starting with 8200 head for Allegany County, this led to an estimate of 45 additional head grown through feedlot but condemned at time of slaughter. I assumed these 45 additional head would not have been included in the USDA statistics for weight of live animals produced in 2005 (40.7 billion lbs). Thus I added these 45 head to the feedlot output resulting in a flux of 8,245 live head out from feedlot to slaughter. The bodies of the 45 head condemned were assumed to go to the landfill lacking other data and this was treated as a terminal or unusable flux of 513 kg N/yr.

I also estimated 39% loss of total mass in discarded body parts from the difference between reported values for total live production and total beef production in dressed carcasses (NASS 2006). This mass was treated as an export of usable medium and most of it is likely rendered into protein products for other uses. Some beef by-products are used in feed and supplements for industrial poultry and hog operations but have been banned for use in beef feed since the 1997 occurrences of mad cow disease (Pollan 2006).

Feedlot

Beef feedlots are examples of confined animal feeding operations (CAFO) that have greatly increased the economic efficiency of beef production while also creating new problems related to manure disposal and animal health with implications for human health as well. Many feedlots have huge numbers of steers, often on the order of 30,000 head (Pollan 2006), in a small central feeding area surrounded by a larger area of land in corn and/or hay production. The surrounding land often also serves as a site of manure disposal and recycling. Salin (2001) reported 700 feedlot operations in ten states in 2000, with the 300 largest managing 74% of feedlot beef production.

The start for characterizing the feedlot compartment was the need to supply 8245 steers to the slaughter and meatpacking compartment as described above. The first step was to account for an estimated 3% that die in feedlots (Pollan 2006). This results in a need for 8500 steers to enter the feedlot compartment.

Average steer weight at the start of feeding was taken as 250 kg (Pollan 2006) and final weight as 570 kg (NASS 2006) thus leading to average weight gain of 320 kg or about 1.36 kg per day over the average time in the feedlot of 235 days (Gregory et al. 1994). Steers are usually 7-10 months old at the start and are sold for slaughter at 14-16 months (Pollan 2006, Gregory et al. 1994). An average weight of 410 kg and 2% N in live cattle were used for estimation of standing biomass N and loss of N due to deaths (treated as respiration or terminal loss to landfill or to be destroyed).

Estimates of N inputs in feed were based on a diet of 75% corn and 25% hay and protein-mineral supplements (Pollan 2006). Using feed data from Hao et al. (2005) provided a value of 51.5 kg N total intake in feed of which 38.7 kg came from corn, 9.8 kg from hay and 3.6 kg from supplements. These estimates result in feed conversion efficiency of 6.7 kg dry matter feed intake per kg of weight gain. This conversion efficiency would be roughly the same for N depending on the values of %N in feed and live animal biomass, and identical if both of these are taken as 2%. Smil (2002) reported an N conversion efficiency of 7 for beef cattle globally and Herring and Bertrand (2002) reported dry matter efficiency of 5.7 for the U.S.

Manure output was estimated by subtracting from total feed intake the amount of N retained in beef cattle weight gain. The resulting figure of 45.1 kg N per head per year of manure N output was very similar to the estimate of 46 kg of Aillerry et al. (2005). Aillerry et al. (2005) also provided estimates of the percentage of manure N lost to runoff and leaching from animal feeding operations. They reported that of total U.S. manure production about 6% of N is lost via runoff and 0.04% is leached into the soil and groundwater. Eghball et al. (1997) reported 3.2% N lost via runoff from cattle manure composting operations in Nebraska. The larger value of 6% was used as it came from data for the U.S. as a whole and was treated as combined export of reactive N via runoff and leaching. The estimate used for manure N emitted to air was 26%; for derivation and sources for this flux see cow-calf operations below. All manure was treated as recycled via application to the agricultural soils used for the same corn, grass and hay production operations of the network. Half the manure N losses were assigned to feedlot (pre-application) and half to soils (after application).

Many inputs integral to industrial feedlots, some of which likely involve N fluxes, were not analyzed. Pharmaceuticals including the antibiotics Rumensin and Tylosin, ingredients in protein supplements such as liquefied fat, vitamins, synthetic estrogen and urea and energy use and fuel combustion for vehicles, grinding and mixing of corn and feeds and other mechanized processes were ignored (Pollan 2006).

Cow-calf Operations

Cow-calf operations produce steer calves for feedlots as well as cows for breeding. Cows are bred or inseminated, carry and birth calves and calves are then nursed, weaned and sold to feedlots. For spring, summer and fall seasons of this annual process cows and calves are on range or pasture land, typically receiving hay and supplemental feed only in the winter. In 2000 Salin (2001) reported 900,000 cow-calf operators nationally marketing 35 million head of cattle.

The start for characterizing the cow-calf operations compartment was the need to supply 8500 steer calves to the feedlot compartment as above. Considering literature values and estimated losses, a steady state herd of 11,100 cows was determined necessary to produce the needed steers as well as some of the replacement breeding cows.

The NASS livestock report (2006) listed calf deaths in 2005 as 6% of the total U.S. calf crop. Tess and Kolstad (2000a) reported that 68% of calf deaths are in the first three days of life and so the average weight of calves lost to death was assumed to be near birth weight and a rough estimate of 50 kg was used. This translated to an estimate of N loss via calf death of 585 kg per year, a relatively small flux. The same NASS report listed cattle deaths as 3.8% of total cattle marketings. Pollan (2006) said 3% of cattle in feedlots die on average throughout the industry. Using the 3% value with 11,100 head of breeding cows gave an estimate of 333 cows dying each year in the sub-system studied. Assuming the average weight of each cow lost was 492 kg (intermediate between yearling average weight of 414 kg and mature weight of 570 kg) yielded a mortality loss of 2997 kg N per year.

The estimated average age at death of breeding cows provided a basis for quantifying needs for replacement of breeding cows. Tess and Kolstad (2000b) also reported that cows were sold when they reached 12 years old. Assuming an even age distribution from 1 to 11 years for the herd of 11,100 cows results in 1010 cows reaching the age limit and being sold each year and an associated N flux of 11,515 kg. A combined total of 1344 cows would need to be replaced each year. I assumed that half of these came from the cow-calf operation itself and the other half were purchased from another operation. These replacements were assumed to be of average yearling weight of 414 kg (Tess and Kolstad 2000b). Nitrogen inputs from replacements cows purchased, and from protein supplements in feed (see below), were treated as imports from outside the network.

The standing stock biomass of cows and calves was estimated from the 11,100 cows and 9,172 calves. For the cows, an average weight of 492 kg was again used. The biomass of calves was estimated assuming an average weight of 125 kg (intermediate between 37.2 kg birth weight and 212 kg weaning weight). Calves becoming replacement breeding cows were estimated to weigh 313 kg (average of weaning weight of 212 kg and yearling weight of 414 kg). For all these calculations all cows and calves were assumed to be 2% N live biomass wet weight basis. NASS (2006) reported that 53% of slaughtered cattle were steers, 1.6% bulls, 31% heifers and 15% dairy and other cows. Since these figures amount to a sex ratio of about 55% males to 45% females that is not too far from 50%, no accounting was done for additional cow-calf pairs needed to supply more males than females. This assumption would likely result in an underestimate of the herd size and the feeding and other input needs for the beef production level studied.

Tess and Kolstad (2000a and 2000b) simulated a cow-calf production system applicable to and with parameters derived from operations in the Northern Great Plains and the Rocky Mountain West as in Montana. Montana is the 7th largest producer of calves for beef feedlots, and the top six calf production states are Texas, California, Missouri, Oklahoma, Nebraska and South Dakota (NASS 2006). Thus estimates for cow-calf production from Montana are likely skewed toward less grazing time and native forage intake and more winter feed or hay and supplements than the actual U.S. average, since the major calf producing states are farther south.

Tess and Kolstad (2000b) reported intakes of native grass, alfalfa hay, grass hay and nutritional supplements for cows and calves and how these vary monthly. They also reported percentage of crude protein (CP) in each of these feeds, which varied from a low of 6% CP in dormant native grass in November and December to highs of 17% and 20% CP in alfalfa hay and protein-mineral supplements, respectively. All forms of crude protein were assumed to be 16% nitrogen and as combined with CP percentages these figures showed native grass to range from 1.0 to 2.6% N, hay from 2.2 to 2.7% N and supplements were 3.2% N. These estimates of N in feed were similar to those of Bahar et al. (2005) who reported grass silage to be 2.2% N.

Summing simulated masses of daily intakes of all feed types for cows and calves provided estimates for annual N intake per cow of 47.2 kg N from grass, 31.2 kg N from hay and 2.7 kg N from protein supplements. Calves ingested approximately 7.1 kg N from grass. Calves also nursed for 7 months of each year, from birth typically in mid-

March to weaning in mid-October, with peak milk yield of 11.2 kg per day on average for five genetic lines (Tess and Kolstad 2000b). Tess and Kolstad (2000a) reported that cows' milk is 3.5% protein and 4% fat. (For comparison USDA (2006) describes commercial whole milk as 3.2% protein and 3.25% fat.) These figures yielded an estimate of a maximum of 13 kg N per year that calves intake, and cows output, via nursing. A lower estimate of 11 kg was used assuming less than peak milk production and intake.

Three estimates for calf weights at weaning and transfer to feedlots were found and the intermediate value of 250 kg of Pollan (2006) was used. Tess and Kolstad (2000b) reported weaned calves averaging 211 kg, and Gregory et al. (1994) reported 285 kg. Sterner and Elser (2002) estimated large mammals as 7.2% N on a dry mass basis. Assuming cattle are 70% water, this translates to 2.2% N on wet weight, live animal basis. Hao et al. (2005) used a value of 1.6% N per unit of weight increase for growing feedlot cattle. An intermediate value of 2% N was used for live weaned calves which could then be used to estimate annual N flux from cow-calf to feedlot operation.

The total cow and calf intake values (from all feed types and milk) of 81 and 18 kg N per year, respectively, were used to estimate N excreted as manure onto rangeland pastures. Estimates of N going into milk, birth of calves, and cow and calf weight gains were subtracted to give 68.4 kg per cow and 13.7 kg per calf available to be excreted as manure. These per head values were scaled up to a total manure N flux estimate. This manure was treated as transferred back to the soil compartment, of which part is associated with the rangeland pasture and part with corn production.

Aillerry et al. (2005) and Eghball et al. (1997) provided estimates of losses of manure N to air and water. Aillerry et al. (2005) reported a 21% loss of ammonia N to air via volatilization from feedlot storage in the Chesapeake watershed (and an additional 7% loss from the field after application). Eghball et al. (1997) reported annual N losses to air of 19%, 32% and 43% during composting in three different years in Nebraska for an average of 31%. An intermediate value of 26% N loss to air was used for both cow-calf and feedlot operations and this was used to split the manure N flux into portions recycled back to soils and exported to air as useable medium. A value of 6% N loss to runoff and leaching was used as above for feedlots. No estimate of N loss to N_2 via denitrification was made. Smil (2002) reported that NO and N_2O emissions from agricultural soils range from 0.5 to 2% of N applied. As for the feedlot, half the N losses to air and run-off were assigned to the cow-calf operation and half to the soils compartment.

No specific estimates were made of N fluxes associated with the backgrounding process. This step is the two-month period when cattle diets are transitioned gradually from grass and hay to corn (Pollan 2006). This is usually done at the cow-calf operation but can be done at the feedlot. The N concentration and total amounts of feed are similar to other estimates and so this lack of detail should not affect estimated N fluxes significantly. It is, however, a very significant aspect of the beef production process as related to ruminant evolution and physiology - ruminants co-evolved with grasses and eating corn alters their digestion radically including changes to acidity and increased susceptibility to bacterial infections (Pollan 2006). Thus the transition to a high corn diet has many implications for industrial agriculture, animal health and the need for antibiotics, the fat content in meat, human health and related issues. Those issues are not addressed here except to cite a recent controversy related to antibiotics use in cattle feed currently in the press (Weiss 2007).

Feed Corn

The history of how corn became the main feed for beef cattle is another interesting story. Pollan (2006) links this evolution, a major change from the older method of raising beef on grass and hay, to both the efficiency corn affords by shortening the time needed for cattle to fatten up to slaughter weight and industrial, systemic need to make use of excess corn production in the U.S.

Constructing the dataset around the corn production process compartment began with the need to supply 328,581 kg N in feed to the feedlot. To estimate a total mass of corn the value of 1.3% N in corn was used from an estimate for corn silage (Bahar et al. 2005) and higher than an estimate of about 1% N in corn kernels (Peterjohn and Correll 1984). It is interesting to note that corn has lower protein and thus N content than grass (estimated at 1.8% N), grass silage (2.2% N) and barley-based feeds (2.4% N, Hao et al. 2005). This seemingly relates to the fact that industrial beef production is geared toward faster weight gain, and that since corn has more carbohydrates than grass and hay it can facilitate more rapid weight gain via increase in fat.

The values found led to an estimate of 25.3 million kg of total corn dry biomass output required for the beef supply chain. Additional values of corn yield of 365 bushels per ha and 25 kg weight per bushel (Baker and Allen 2006) combined with values of N content in corn and total N required provided an estimate of 2,723 ha of land needed for corn production. Building the data for the corn compartment was done in concert with quantifying fluxes for the soils compartment as they are closely linked via application and uptake of N from fertilizer, manure and other sources.

I assumed that the corn production was geared mainly to produce kernels and thus that 50% of the non-kernel portion of the plants were returned to the soil as litter. The remaining half of stalk mass and a small pest loss were labeled as exports. Input from seeds was taken as 1% of kernels harvested or about 3300 kg N total. Other usable losses due to waste, wind blown pollen and saved seeds were not included due to lack of data but are likely relatively small fluxes. A terminal loss of 4000 kg was added based on a very rough estimate of corn lost to unusable waste. Biomass for this compartment was treated as corn reserves and was estimated as 10% of annual production.

Grass and Hay

The starting point for the production of grass and hay feeds was the need to provide 907,762 kg in N in grass and hay to both feedlot and cow-calf operations. Using Pollan’s (2006) estimate of 10 acres of pasture or range land required for each calf produced led to a need for 35,000 ha for the 8500 calves output from the cow-calf unit.

One eighth of the grass pasture and hay land was assumed to be nitrogen fixing alfalfa. Haby et al. (2006) reported 80 to 220 kg N per ha of atmospheric N-fixation in alfalfa hay in Texas. The mid-point of this range (151 kg N/yr) was used for N input for alfalfa. An estimate of 40 kg N per ha uptake for non-leguminous grasses was also used. Half of the annual grass and hay production was assumed to occur belowground and this estimated value was used both as root litter production that flows to soils and as standing stock of the grass-hay system (i.e., a biomass portion of roots that survive through winter). Litter flux was routed as recycling back to the soils compartment. Losses due to pests were set at 5% and most of this was treated as export of good medium with just 5000 kg lost as terminal, unusable output.

Soils

The soil compartment represented agricultural soils of corn, grass pasture and hay operations needed for forage and feed. The estimates of 2,723 ha of corn production and 35,000 ha for pasture, range and hay were summed to 37,723 ha of soil.

All manure from feedlot and cow-calf operations were inputs to soils. Ferguson et al. (2005) reported that 30% of added manure is available for plant uptake in the first year. This value was used and the remaining 70% of manure N was routed as input to the organic matter N pool. Input of N via atmospheric deposition was set at 4 kg N per ha, an intermediate value of many surveyed by Fiscus (2007b in preparation). I assumed an N mineralization rate from organic matter decomposition of 50 kg per ha N, less than Aber et al. (2004) value of 84 kg N per ha for forests. A small and rough estimate of 5000 kg or about 0.1 kg N per ha was treated as lost to denitrification.

Pimentel and Kuonang’s (1998) estimates of one ton per ha soil lost to erosion for grass hay and 10 tons for corn were used. Then using an intermediate value 0.1% N in agricultural soil (range of 0.05% at depth to 0.5% N in surface organic matter, Fiscus 2007a in preparation) led to a relatively small flux of N lost via soil erosion. To supply the total N needs required the N fertilizer input was set at 700,000 kg. This amounts to 257 kg N per ha considering just the corn production but much less considering the land in pasture and hay.

Fertilizer

The start for estimating fluxes and stocks associated with nitrogen fertilizer began with the need to supply 700,000 kg N to soils for corn and hay feed production as above. A very rough industrial process was considered in which 1) natural gas (CH_4) reacts with water to generate hydrogen gas (H_2) via the steam reforming process (Wikipedia 2007b), 2) hydrogen gas (H_2) reacts with atmospheric nitrogen gas (N_2) to produce ammonia (NH_3) via the Haber-Bosch process (Wikipedia 2007a), 3) ammonia (NH_3) reacts with atmospheric oxygen (O_2) to form nitric acid (HNO_3) (Alley and Wysor 2005), and 4) nitric acid reacts with additional ammonia to form ammonium nitrate (NH_4NO_3) (Alley and Wysor 2005).

Using the mid-point (15%) of the reported yield efficiencies of 10-20% (Wikipedia 2007a) provided estimates of input N from atmospheric N_2 as well as output N_2 passing through as not converted to ammonia. The 85% of N_2 not converted was treated as a respiration rather than an export of useful medium, but this choice is debatable. Using the proportion of ammonium nitrate as 34% N a value of 2.06 million kg of total NH_4NO_3 mass was estimated as needed to supply 700,000 kg of fertilizer N. This total mass value was also used to estimate NOx emissions from nitric acid used in the industrial manufacture of ammonium nitrate in the U.S. An average value of emissions limits of 3.6 lbs of NOx per ton of nitric acid was used based on the Lake Michigan Air Directors Consortium (LADCO 2005) white paper. This paper stated, "The majority of the NOx non-fuel combustion process emissions are from nitrogen-based fertilizer manufacturers operating nitric acid plants" (LADCO 2005). I assumed that no fuel-related or combustion NOx emissions are generated in the use of natural gas in the fertilizer production process, as the temperature of the reaction was reported as 700-1100 degrees C (Wikipedia 2007a), well below the lower limit for production of NOx via thermal process of 1600 degrees C (Wikipedia 2007c).

Galloway et al (2004) state that about 6% of global N fertilizer produced is not consumed. This figure was used to estimate standing stocks as reserves of 6% of the annual production and input to the beef supply chain being modeled.

Wastewater Treatment

Rough estimates for transformations occurring at the wastewater treatment plant (WWTP) were developed using data from EPA's National Pollutant Discharge Elimination System data (NPDES 2007) for the Cumberland, MD plant. This data showed an average total N export from 2003 through March 2006 of 388 kg N per day, which scales up to about 142,000 kg N per year. The average total N concentration during this time was 7 mg / L, and the average total outflow of treated wastewater reported for years 2000-2001 was 10.4 million gallons per day (mgd).

The fact sheet associated with the NPDES permit for Cumberland's WWTP includes this description of the plant (MDE 2001):

> The plant utilizes two bar screens, two grit removal units, four primary settling tanks, six BNR [biological nutrient removal] basins, four secondary settling tanks, chlorination and de-chlorination to treat about 10.28 mgd of wastewater (1/99-4/01). The plant has been recently upgraded to Biological Nutrient Removal. Screenings from the bar screen are disposed of in a landfill every two weeks. Sludge from the primary settling tanks goes to the gravity thickeners. Secondary sludge is mechanically thickened and dewatered. Sludge is then stabilized and applied to land. The plant discharges directly into the North Branch Potomac River. At the outfall location the river is about 300 ft. wide and flowing with a velocity of 1 ft/esc. [Assume this is 1 ft/sec.]

A report on the basic steps in the wastewater treatment process (EPA 1998) says secondary wastewater treatment removes about 85% of organic matter in sewage mainly via activated sludge process in which bacteria break down the organic matter into "harmless by-products". A report to Maryland Department of the Environment (MDE 2007) stated that Cumberland uses a "step feed" biological nutrient removal (BNR) system. Jeyanayagam (2005) reported step feed BNR can achieve effluent N concentrations of 6-8 mg/L. The MDE report (2007) also used a value of 38 mg/L for total Kjeldahl nitrogen (TKN) in influent water coming in to Maryland WWTP's. A manual on the use of constructed wetlands to treat municipal wastewater (EPA 1999) lists typical wastewater influent TKN ranges from 28 to 50 mg/L and influent total nitrogen (TN) ranges of 41-49 mg/L. The values of 38 mg/L N in influent and 7 mg/L N in effluent were used to estimate 82% removal of N in the WWTP and delivery of 18% of influent N to the Potomac River.

The 82% of sewage N removed was assumed to go in three equal proportions to N_2 gas via denitrification, ammonia gas emission and application of biosolids to land. The latter was routed as an export and not applied to the soils compartment for beef production. No such applications were included in the present study as the vast majority of beef production occurs in the west and mid-western U.S., and this was deemed too far for transport of biosolids from the wastewater treatment plant for the human population in Allegany County.

Human Mortality

Very rough estimates were made of N fluxes associated with human death. I assumed an even age distribution from ages 1 to 75, and life expectancy of 75, such that 1,000 people die each year on average in Allegany County. An average weight at death of 50 kg and 2.5% N content in humans led to a flux of 1250 kg N per year. The N embodied in 1,000 people was treated as routed half to cemeteries (terminal, unusable loss to soils) and half to cremation (an export of usable medium to atmosphere). No estimate of intra-compartment N flux associated with human infants nursing was made.

Natural Non-human Datasets for Comparisons

Chesapeake Bay

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. This aggregated dataset is also in units of mg C/m^2 for stocks and mg C/m^2/day for fluxes. 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.

Florida Everglades Cypress Swamp

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.

Network Comparison Metrics

The main goal was to compare human and natural ecological networks in meaningful ways and to assess the implications for environmental sustainability of humans. Within ecological network analysis are many tools, techniques, analytical outputs and indices available for characterizing the salient properties of networks. From among these many options eight 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
2. Degree and structure of material cycling
3. Information indices including ascendency, overhead and capacity
4. Connectance
5. Number of roles and the “window of vitality”
6. Residence times
7. Total contributions and dependencies
8. Stock-flux and stock-respiration scaling

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 methods will be described next.

Trophic Levels and Efficiencies

All networks were characterized according to the trophic concepts of Lindeman (1942) via the techniques of Ulanowicz and Kemp (1979) and Ulanowicz (1995). These methods apportion the feeding activities of all species or compartments among a series of integer trophic levels with consideration of material cycling. For this analysis compartments were distinguished between those representing living populations or systems versus abiotic compartments. For the human-beef network analysis, four compartments that combine both living and non-living (i.e. industrial and mechanical) functional aspects were treated as living. These were 1) slaughter and meatpacking, 2) transportation, 3) retail, and 4) home refrigeration and cooking. 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 a 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 (among others) raises important questions and suggests a need for examination of the extension of ecological network analysis to human and industrial systems. These are explored in the discussion section.

The trophic aggregation algorithm identifies and removes any cycles that exist entirely among the living compartments prior to assigning trophic levels (Ulanowicz

2002b). Cycles via detritus, soils, sediments and abiotic pools are not removed. Effective trophic level is a weighted average of the amounts of feeding that each species does at each level. This technique provided effective trophic levels for all compartments in all networks with special focus on those for bluefish in the full Chesapeake Bay networks, carnivorous fish in the aggregated Chesapeake Bay network, alligators, black bears and Florida panthers in the Everglades network and humans in the human-beef network. Trophic efficiencies – defined as “the ratio of the input to a trophic level to the amount that level passes on to the next” (Ulanowicz 2002b) - were also calculated and compared. As noted in the humans-beef network methods section, not all possible nitrogen fluxes were quantified for industrial compartments. Fluxes of N associated with fossil fuel use and human workers were omitted. These omissions would likely result in over-estimates of the trophic efficiencies of these human compartments relative to true or total efficiencies and relative to natural networks.

Degree and Structure of Material Cycling

Material, nutrient, energy and biogeochemical cycling are all central concepts in ecosystem ecology. One of many classic papers that inspired comparison of cycling between human and natural systems as crucial for understanding and achieving sustainability came from Likens et al. (1970). They hypothesized “intrasystem cycling“ as one of two systemic organizing principles responsible for the homestatic properties of forested watershed ecosystems (the other being functional balance between autotrophy and heterotrophy). Ecological network analysis provides means to compare the total and proportional amounts of cycling, the number of cycling loops, the lengths (number of links) of cycling pathways, and cycled flow relative to acyclic flow. The proportion of total system flow that is recycled comes from the Finn cycling index (Ulanowicz 2002b), and this total flow was also reported as divided over cycles of varying path lengths. The latter details are useful in providing knowledge of whether recycling occurs via long and slow versus short and fast pathways, and this can yield knowledge on the eutrophication and disturbance status of ecosystems (Ulanowicz 1997).

In the humans-beef network studied, humans do not participate in any material cycles (i.e., in terms of flows of dietary nitrogen). This would change and cycling would increase if outputs from wastewater treatments plants were included, as in quantifying sludge or biosolids applications onto farm soils involved in beef production at the national level.

Information Indices and Ascendency

Perhaps the most synthetic metrics available from ecological network analysis are the whole-system indices based on information theory. These metrics are powerful in their generality and robustness and along with the underlying theory they are largely responsible for the fact that we can compare such diverse networks in meaningful ways. The development of these metrics and associated theory and application spans 35 years and continues today (Ulanowicz 1972, Bondavalli and Ulanowicz 1999, Ulanowicz in preparation).

Six major concepts and associated quantitative indices were used for network comparisons: ascendency, average mutual information, capacity, entropy, overhead and redundancy. These are next defined briefly as based on Ulanowicz (2002b) and Ulanowicz (2004).

Network or ecosystem *ascendency* is a measure of the potential for competitive advantage over other real or possible network configurations. Ascendency is the product of system size (total system throughput) times a measure of system coherence (the average mutual information of the stocks and flow structure). Thus its units are flow-bits, where flow is in units of mass of material or energy flux per unit time. The *average mutual information* (AMI) quantifies the degree of organization or constraint in the network structure. It is measured in bits.

Network development *capacity* represents the total potential for organization as related to the actual diversity of network nodes, stocks and flows. Capacity is calculated by multi-plying the total system throughput by the system *entropy* as based on the Shannon Wiener formula. Capacity is an upper bound on ascendency, and entropy is an upper bound on AMI. The difference between network orderliness and coherence (ascendency and AMI) and its upper bound (capacity and entropy) is the *overhead*. Overhead quantifies the non-constrained or reserve network structural capacity that may provide a basis for reorganization in times of disturbance or changing environment. Overhead is subset into four components - overhead associated with imports, exports and dissipations (respirations), and that associated with flows occurring along duplicate and parallel pathways. This latter component is the network *redundancy*.

In EcoNetwrk software (EcoNetwrk 2007) ascendency and capacity are reported on internal and total bases as well. This enabled comparison of ascendency to capacity ratios via both internal and total perspectives. The export overhead and dissipative overhead – both as proportions of network capacity - were highlighted for comparisons relevant for sustainability as linked to excess nitrogen export from human-dominated landscapes to surface waters.

Connectance

Ecological network analysis provides three means to characterize the effective number of connections per compartment and between any two compartments. The *overall connectance* considers all links including exogenous transfers (imports, exports and dissipations). The *intercompartmental connectance* characterizes only the endogenous (intra-system) exchanges. The *foodweb connectance* treats only those transfers among the living network compartments. The overall connectance is also one of the two metrics used to define the window of vitality, as in the next section.

Network Roles and the “Window of Vitality”

Ulanowicz (2002a) has found that all real natural ecosystems thus far analyzed exhibit network properties within a narrow range of all possible network configurations. This small bounded region or “window of vitality” places each system on a plot of the number of network roles (y axis) versus the effective connections per node (x axis, the overall connectance above). To calculate the number of roles, one raises 2 to the power of the average mutual information (Zorach and Ulanowicz 2003). While the number of network roles is related to the highest effective trophic level, these are not identical. A limit of about 4.5 for both roles and effective trophic levels has been observed (Ulanowicz 2002a, Zorach and Ulanowicz 2003). This limit fueled one of the central hypotheses of the comparative network study – that human food webs would have more than 4.5 roles and trophic levels and thus fall outside the window of vitality with major implications for sustainability. The ways in which roles and effective trophic levels differ and diverge is examined in the discussion.

Residence Times

Several workers report on the importance of residence times for understanding ecosystems, their developmental and dynamic trends over time and their central organizing principles. Ulanowicz and Baird (1999) reported how compartments with longer residence times increase the total network ascendency or coherency. Fath et al. (2001) also found residence times to be a key link in understanding goal functions or orientors for ecosystems self-organization. They showed that two widely reported but seemingly contradictory ecosystem tendencies for increasing (or maximized) system storage and increasing dissipation can be reconciled as long as network residence times also increase.

Residences times were calculated for fluxes of carbon or nitrogen for all compartments. This was done by dividing compartmental stock or biomass by total compartmental throughput yielding a measure in units of time. These values provided a means to compare how human and natural networks differ based on ranges, distributions and intra-network relationships of compartmental residence times.

Total Contributions and Dependencies

Two useful sets of output from ecological network analysis are the *total contribution coefficients* and the *total dependency coefficients* (Szyrmer and Ulanowicz 1987). These analytical results helped make it possible to compare full food webs (e.g., Chesapeake By and the Florida Everglades) with the partial food web of the beef supply portion of the U.S. human system. The following descriptions are taken from Ulanowicz (2002b).

The *total contribution coefficients* are reported in a matrix that quantifies the fraction of the material leaving any given compartment that eventually enters any another compartment over all direct and indirect pathways. Thus, for example, one can ascertain what proportion of all the nitrogen in gross beef production leaving the feedlot eventually enters the human compartment as beef N ingested. These values enable measures of system efficiencies, such as kg N in fertilizer needed to provide 1 kg N in beef for human consumption. Diagonal entries in the contribution coefficients matrix indicate how much each compartment self-stimulates or self-feeds over all pathways. As mentioned for cycling analysis above, this value is zero for humans in the humans-beef system since there is no recycling of N in human wastes or deaths back to any other compartments of the beef network.

The *total dependency coefficients* are also reported in a matrix of cells linking all compartments in the network. Each entry quantifies the proportion of the total ingestion by any given compartment that passed through any other compartment in the whole system process. Thus one can know what percentage of each species' diet any other species or compartment mediates. By looking at columns in this matrix, for example for humans, bluefish or alligators, one can see the extended and indirect links required to provide the direct prey items and overall diet for each species. High dependency on one or more compartments could indicate vulnerability as disruption or loss of those mediating compartments could have a large impact on one's food supply. Conversely, low individual compartmental dependencies, perhaps as associated with higher redundancy and multiple pathways by which one's diet is provided, should indicate greater food supply security, stability and resilience to disruption.

Stock-flux Scaling

The final basis for network comparison was to use plots of compartmental biomasses or stocks versus 1) compartmental respiration flows and 2) total compartmental throughput flows. These relationships were of interest based on work by Ulanowicz (1991) who first reported power law relationships in the distribution of ecosystem flow magnitudes. Prior work on forest soils (Fiscus 2007a in preparation) also found power law relations in depth profiles of stocks of soil carbon, nitrogen and organic matter. Using the data for stocks and the two fluxes, log-log plots were made and linear regression lines calculated. These regression lines provided slopes and intercepts that were compared across the human and natural networks.

Results

The first result of the research project was the dataset for the beef supply chain as a sub-network of N flux in the U.S. human food web. This is presented in diagram form in Figure 4.1 and matrix form in Appendix B. Figure 4.1 shows only internal flow links, but Appendix B also includes the quantities of N in imports, exports, respirations and standing stocks associated with each compartment. 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 this would change somewhat if fuller accounting were done, such as including flux of N in biosolids applied to farmland nationally.

Effective Trophic Levels and Trophic Efficiencies

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). Comparisons of carbon and nitrogen networks for 13 species in the Chesapeake Bay showed most to be very similar in effective trophic level for these two major ecological currencies. Effective trophic levels reported in Table 4.2 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 based in part on treating 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. 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 home refrigeration and cooking compartments, each of which acts as its own trophic level (Table 4.3). 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. The high efficiencies apparently reflect the benefits of technology as well as the energy subsidy that fossil fuels provide. Comparisons of trophic levels for carbon and nitrogen networks in the Chesapeake Bay showed very similar efficiencies at all levels.

Degree and Structure of Material Cycling

Table 4.4 reports results for the number of distinct material cycle pathways, proportion of total throughput that is recycled (Finn cycling index) and longest cycle path

Table 4.2. 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)	Compart-Ment	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	homerc	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	cowcalf	3.0
striped bass	3.86	4.61			turtles	2.82	grasshay	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		

Table 4.3. 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	

Table 4.4. 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

lengths for each of the five networks. These results are very different for C versus N in the Chesapeake Bay, with many more distinct cycling pathways and more than twice the proportion of material recycled for N compared to C. The human-beef sub-network (12 compartments) was most similar to the Chesapeake Bay aggregated C network (15 compartments) for longest cycle path lengths and proportion of material cycled. Compared to the other C networks, the human network showed a greater proportion of cycled flow but over fewer pathways and shorter path lengths. Compared to the full Chesapeake N network, the human-beef supply chain had less than half the proportion of N flow as recycle flow and again over far fewer cycles and far shorter longest path lengths.

Information Indices

Results for many comparisons of information indices are in Table 4.5. 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 measure of the human-beef N network (3.53), notably less than the non-human C and N networks (range of 4.47 to 4.92).

Comparisons for overhead measures also showed differences. 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 to 0.42). The human-beef network also had

Table 4.5. Comparisons of network information indices, connectance and roles.

Network Atttribute	Chesapeake Bay full C	Chesapeake Bay full N	Ches. Bay Aggregated C	Florida Ever-glades C	Humans and Beef	Human versus others
Information Indices						
TST	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	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 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 easily directly comparable (e.g., total system throughput, ascendency, capacity, redundancy) as they represent vary different units. The ratios above provide a means for comparison given different network dataset units.

Connectance

For all three of the connectance measures the human-beef network showed lower values than the non-human networks (see Table 4.5). Overall connectance was 1.75 links per node compared to a range of 1.85 to 2.68 in the Chesapeake Bay and Everglades systems. Intercompartmental and foodweb connectance were similarly lower.

Network Roles and the "Window of Vitality"

Using the values for AMI for each network, the number of network roles was calculated (Table 4.5). 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 hypothesis. Thus based on this measure the human-beef supply chain is organized in similar topological fashion to all other non-human ecosystems thus far evaluated with these metrics.

Residence Times

Residence times for N and C in all the human-beef compartments and several important compartments in the Chesapeake Bay and Everglades ecosystems are shown in Table 4.6. Residence times for N in the human-beef network ranged from 0.0005 years (about 4 hours) 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 around 80 days.

Residence times for N in the Chesapeake Bay species ranged from about 18 hours 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 hours 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.

Table 4.6. Residence times (days or years) for examples species and compartments.

Chesapeake Bay full			Ches. Bay aggregated		Florida Everglades		Humans and beef	
Species	Res. times for C (days)	Res. times for N (days)	Species	Res. times for C (yr)	Species	Res. times for C (days)	Compart-ment	Residence times for C (days)
bluefish	14.6	7.8	carnivorous fish	10.3	alligator	55.1	humans	83.0
croaker	10.8	12.1	benthic invert. carn.	3.4	snakes	48.0	homerc	2.0
catfish	11.2	14.2	deposit feeders	1.4	woodstork	0.4	retail	1.0
spot	7.9	9.7	pelagic production	0.6	owls	4.1	transport	2.0
summer flounder	15.3	7.9	benthic production	0.2	kites/hawks	4.1	slaughter	0.2
white perch	18.2	9.7			Florida panther	24.7	feedlot	53.0
hogchoker	10.0	12.3			bobcat	21.1	cowcalf	58.1
striped bass	12.9	8.7			turtles	41.7	grasshay	98.1
blue crab	3.4	2.3			black bear	25.1	corn	19.5
bay anchovy	3.0	5.6			crayfish	60.8	fertilizer	3.3
menhaden	7.3	9.8			terrestrial ins.	15.1	soil	8829.7
zooplankton	0.2	0.4			understory	167.5	WWTP	0.3
phytoplankton	0.6	0.8			phytoplankton	0.2		

Total Contributions and Dependencies

The total contributions into and out from each of a set of example species are shown in Table 4.7A and 4.7B respectively. The values in Table 4.7A 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.

Table 4.7B lists the contribution coefficients taken 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. Humans are not included 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, this table lists the guild of species that decompose each of the focal species thus making the nutrients embodied in them as organisms and in their wastes available for future employment in the living ecosystem. It is interesting that 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

Table 4.7A. Contribution coefficients – direct and indirect network contributions in to focal species. LT = Link type, D)irect or I)ndirect.

Chesapeake Bay Full C			Florida Everglades C									Humans and beef N		
Bluefish			**Alligator**			**Black bear**			**Florida panther**			**Humans**		
Species or Cpt.	Contrib.	LT	Species or Cpt.	Contrib.	LT	Species or Cpt.	Contrib.	LT	Species or Cpt.	Contrib.	LT	Species or Cpt.	Contrib.	LT
Spot	0.02120	D	L Fish	0.384	D	Hogs	0.0410	D	Hogs	0.1360	D	home-rc	0.900	D
Menhaden	0.00685	D	Salamanders	0.382	D	Rabbits	0.0101	D	Arma-dillo	0.0478	D	retail	0.887	I
Bay anchovy	0.00142	D	Fish PC	0.254	D	Deer	0.0010	D	Rac-coon	0.0313	D	transport	0.879	I
Nereis	0.00010	I	Salam. L	0.211	D	Snakes	0.0002	D	Deer	0.0065	D	slaughter	0.807	I
Other Polychates	0.00006	I	L Frog	0.191	D	Turtles	0.0001	D	Rabbits	0.0051	D	feedlot	0.182	I
Zooplankt.	0.00005	I	M Frog	0.171	D	Alligators	0.0001	D	Mice & Rats	0.0002	D	corn	0.104	I
Macoma	0.00003	I	Snakes	0.133	D	Terrst. I	0.0001	D	Terrst. I	5.04E-05	I	grass-hay	0.040	I
Suspended POC	0.00003	I	Fish HO	0.126	D	M Frog	0.0001	I	Roots	2.80E-05	I	cow-calf	0.036	I
Bacteria in Sed. POC	0.00002	I	S Frog	0.118	D	L Frog	0.0001	I	L Frog	1.87E-05	I	soil	0.034	I
Sed. POC	0.00002	I	Tadpoles	0.118	D	Tadpoles	0.0001	I				fertilizer	0.005	I
Ciliates	0.00002	I	Turtles	0.099	D									
Fish larvae	0.00002	I	Rabbits	0.078	D									
Bacteria in sus. POC	0.00002	I	Lizards	0.077	D									
Ctenophor.	0.00001	I	Epiphytes	0.043	I									
Phytoplank.	0.00001	I	Passeriformes onniv.	0.041	I									
			Passeriformes pred.	0.033	I									
			Galliformes	0.030	D									
			Mice & Rats	0.030	D									
			Egrets	0.027	D									

Table 4.7B. Total contributions out from focal species to receiving species or compartments.

Chesapeake Bay Full C		Florida Everglades C					
Bluefish		**Alligator**		**Black bear**		**Florida panther**	
Species or Compartment	Contrib.	Species or Compartment	Contrib.	Species or Compartment	Contrib.	Species or Compartment	Contrib.
Sediment POC	0.48400	Vertebrate detritus	0.939	Vertebrate detritus	0.365	Vertebrate detritus	0.220
Bacteria in sediment POC	0.48300	Labile detritus	0.555	Labile detritus	0.216	Labile detritus	0.130
Other polychaetes	0.14100	Living sediment	0.467	Living sediment	0.181	Living sediment	0.109
Macoma spp.	0.06290	Refractory detritus	0.294	Refractory detritus	0.114	Refractory detritus	0.069
Meiofauna	0.03980	Terrestrial insects	0.285	Terrestrial insects	0.111	Terrestrial insects	0.067
Neries	0.02760	Living POC	0.091	Living POC	0.035	Living POC	0.021
Crustacean deposit feeder	0.01620	Opossum	0.040	Opossum	0.016	Opossum	0.009
Blue crab	0.00869	Snakes	0.036	Vultures	0.006	Vultures	0.004
Spot	0.00054	Turtles	0.030	Lizards	0.005	Lizards	0.003
Catfish	0.00025	Vultures	0.017	Aquatic Insects	0.005	Aquatic I	0.003
White perch	0.00016	Lizards	0.014	Crayfish	0.005	Crayfish	0.003
Hogchoker	0.00010	Aquatic I	0.014	Prawn	0.004	Prawn	0.003
Bluefish	0.00001	Crayfish	0.013	Fish HO	0.003	Fish HO	0.002
		Prawn	0.011	Alligators	0.001	Alligators	0.001
		Alligators	0.010				

carbon, and opossum. The ranked contributions then vary but all include vultures, crayfish, lizards and alligators.

Total dependency coefficients are listed in Table 4.8. 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. The link types (direct or indirect) are again listed. 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.

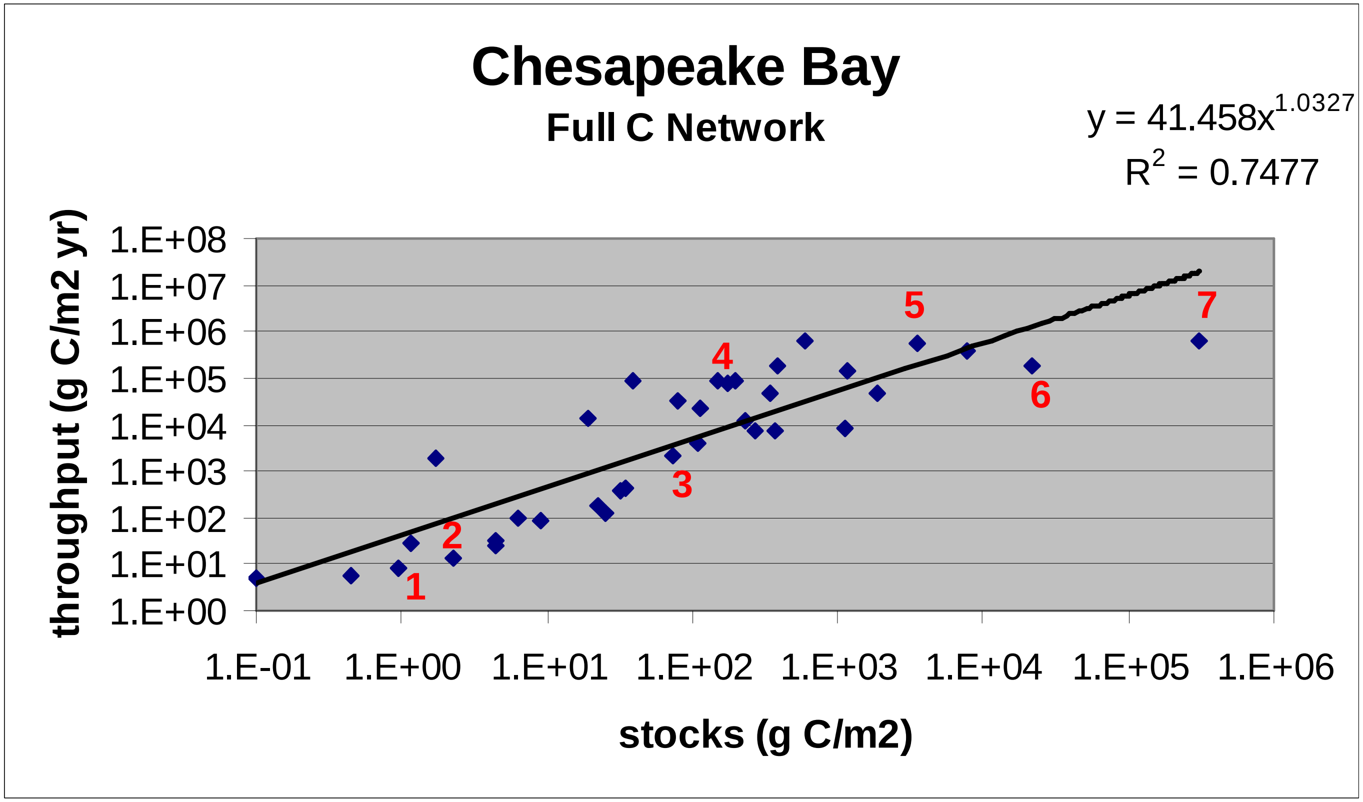
Table 4.8. Dependency coefficients. Proportion of total ingestion by focal species that passes through other species or compartments. LT as in Table 4.7A.

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									

Stock-flux Scaling

The relationships of standing stocks to total compartmental throughputs are depicted in Figures 4.2 through 4.6. These graphs all show reasonably strong linear log-log relationships but vary widely in scaling exponents (associated with the slopes of regression lines) and regression line intercepts. Similar analyses of stock versus respiration fluxes were done for the full Chesapeake Bay C and Everglades C networks, also resulting in strong log-log linear relationships, but they are not reported here.

Stock-flux scaling relationships for the Chesapeake Bay C and N networks (Figures 4.2 and 4.3) were very similar with scaling exponents of 1.03 and 1.00 respectively. The human-beef (Figure 4.6) and aggregated Chesapeake Bay C (Figure 4.4) networks displayed the smallest scaling exponents, resulting in flatter slopes to the linear regression lines, with values of 0.31 and 0.60 respectively. The human-beef network stock-flux scaling also reflects the very different throughput rates and residence times of the industrial and agricultural/ecological segments of this network. The most efficient commercial and industrial compartments all plotted together in the lower left region of the graph.



1 = croaker, 2 = bluefish, 3 = Bay anchovy, 4 = zooplankton, 5 = phytoplankton, 6 = dissolved organic carbon (DOC), 7 = sediment particulate organic carbon

Figure 4.2. Stock-flux scaling for the full Chesapeake Bay carbon (C) network. Equation for log-log linear regression line and R^2 shown on the graph. Selected compartments labeled.

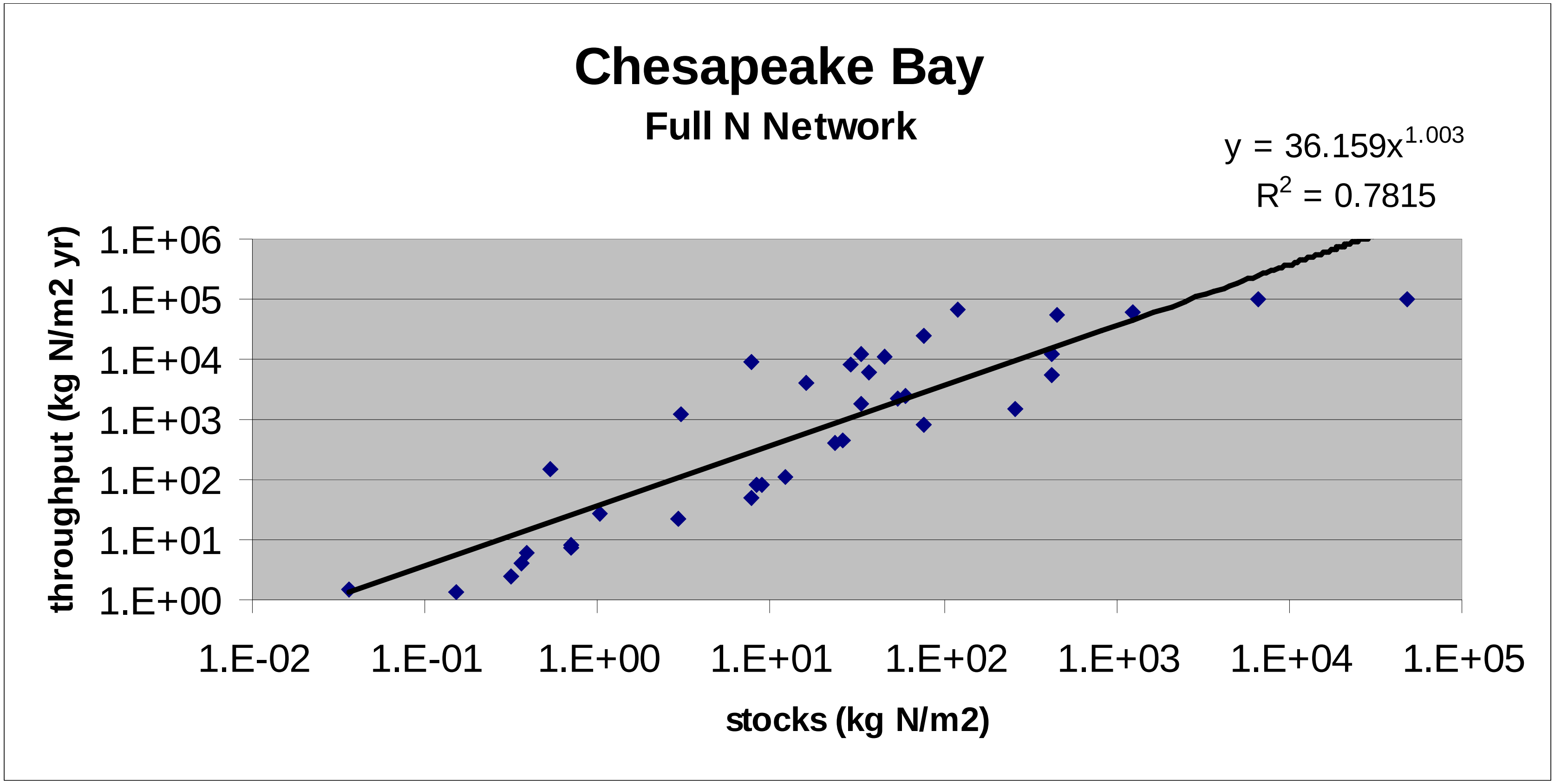


Figure 4.3. Stock-flux scaling for the full Chesapeake Bay nitrogen (N) network. Equation for log-log linear regression line and R^2 shown on the graph.

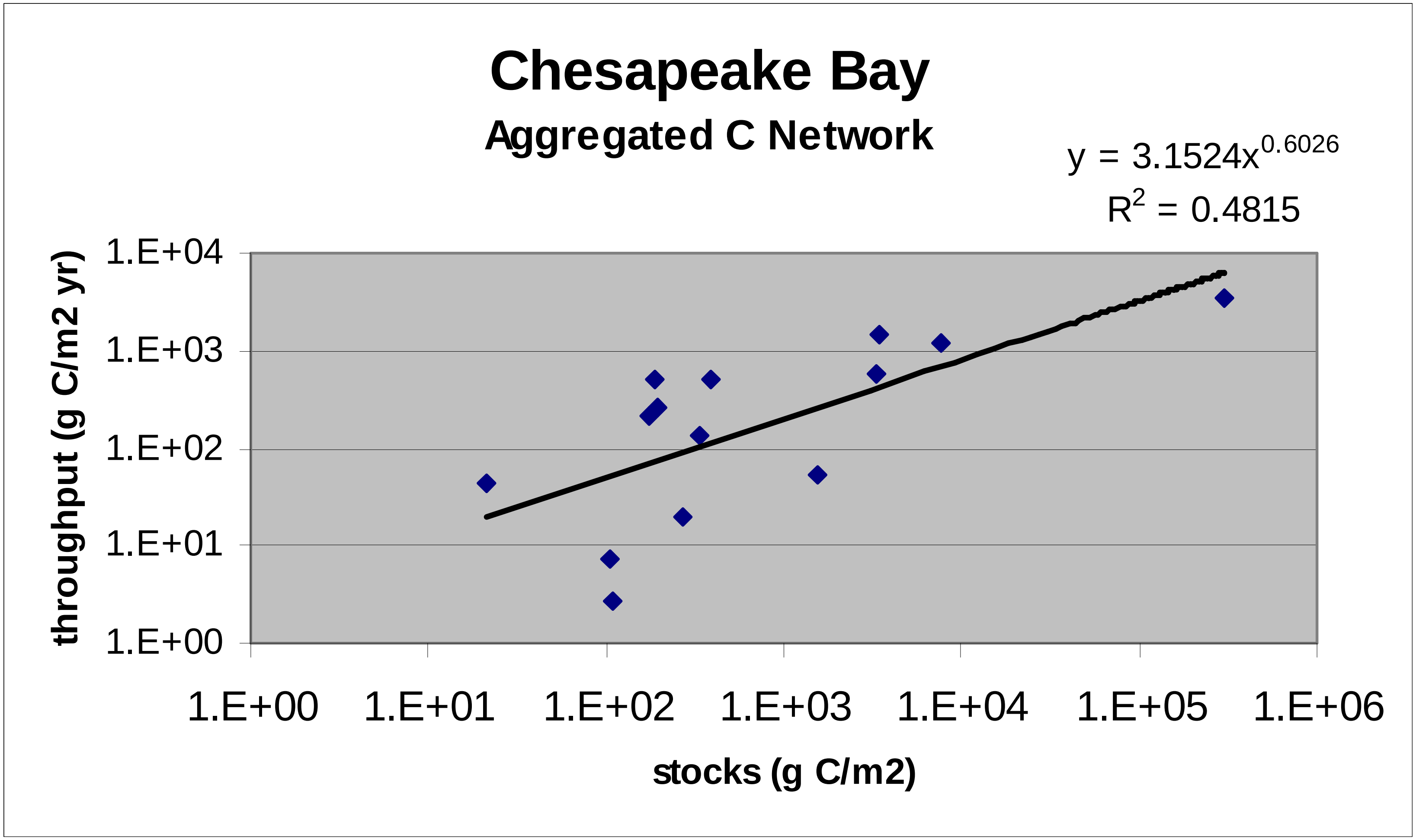


Figure 4.4. Stock-flux scaling for the aggregated Chesapeake Bay carbon (C) network. Equation for log-log linear regression line and R^2 shown on the graph.

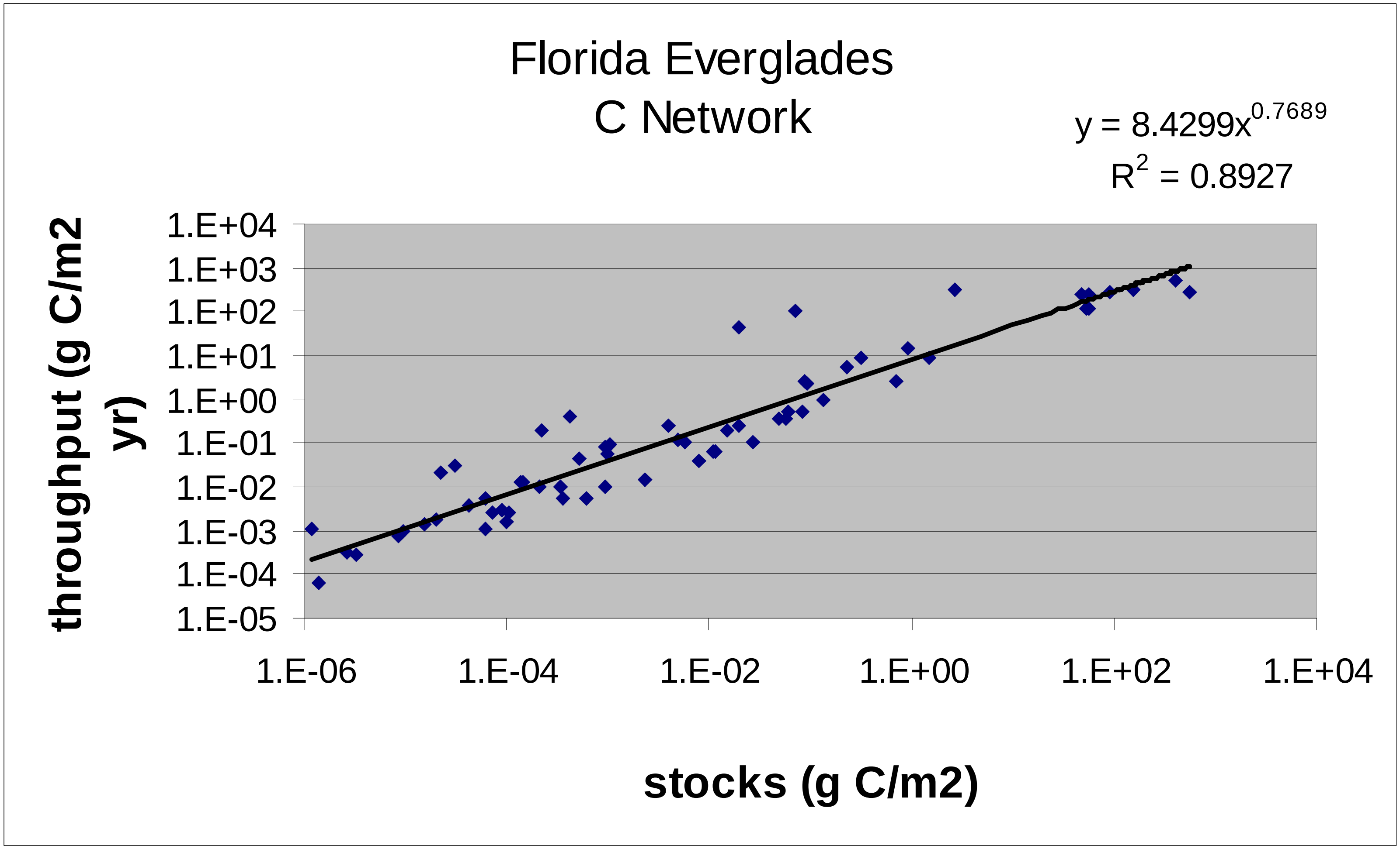
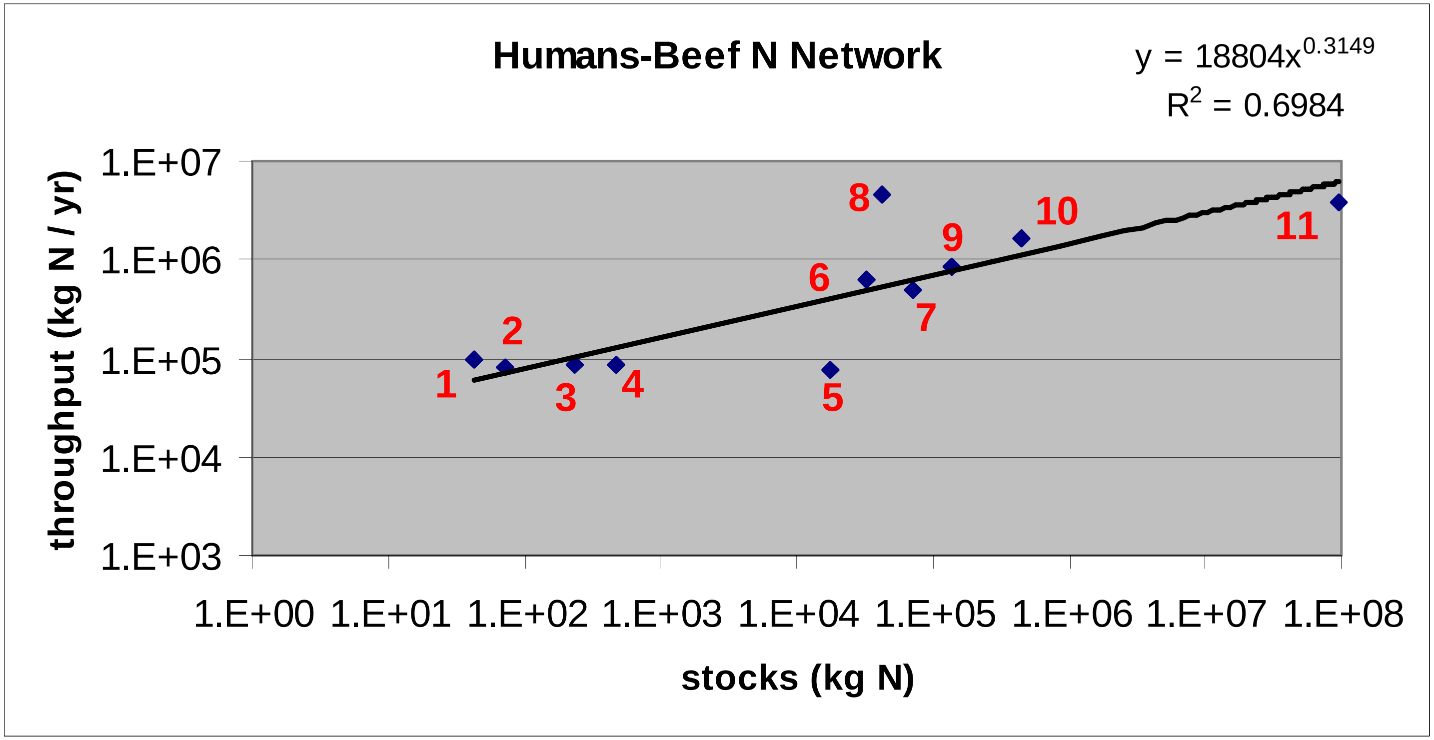


Figure 4.5. Stock-flux scaling for the Florida Everglade carbon (C) network. Equation for log-log linear regression line and R^2 shown on the graph.



1 = slaughter, 2 = WWTP, 3 = retail, 4 = home refrig. and cook, 5 = humans,
6 = corn, 7 = feedlot, 8 = fertilizer, 9 = cow-calf, 10 = grass-hay, 11 = soils

Figure 4.6. Stock-flux scaling for the humans-beef nitrogen (N) network. Equation for log-log linear regression line and R^2 shown on the graph. Compartments labeled. Transportation compartment hidden under point 4, home refrigeration and cooking.

For all networks those compartments with the highest standing stocks and fluxes plotted in the upper right corner, those with lower stocks and fluxes at the lower left corner and intermediate species in the middle. This usually corresponded to plants, soils and sediments plotting in the upper right region, rare species and higher trophic levels plotting in the lower left region, and intermediate trophic levels, generalists and species/compartments with moderate populations or masses plotting in the middle. Some of these details are shown in Figures 4.2 and 4.6 in which the species and compartments are labeled.

Discussion and Conclusions

This report presented results of comparative network analyses for human and non-human ecosystems as part of a larger project to characterize the necessary and sufficient organizational principles for environmental sustainability. One of the goals was to develop a network basis for distinguishing between two fundamentally different types of ecosystems. Allenby and Richards (1994) characterized three idealized industrial ecosystem types. Their Type I ecosystem operates with the greatest boundary flux and linear throughput, least material recycling, highest input of non-renewable resources and highest output into finite waste sinks, all analogous to traditional industrial systems. Their Type III ecosystem shows the highest degree of material recycling, no input of non-renewable resources and no output into finite waste sinks, which they pose as analogous to natural ecosystems, albeit as generalized to extremes of recycling. Finally, their Type II ecosystem is intermediate between Types I and III for recycling, resource inputs and waste outputs. One of the original hypotheses for this study was that ecosystem networks for human systems would tend toward the industrial Type I and networks for natural systems would tend toward Type III.

An additional working idea was that these fundamentally distinct ecosystem types would be causally linked to similarly distinct types of dynamic behavior over time. The Type I industrial ecosystem was predicted to cause (and perhaps be caused by, as in a mutually causal relationship) dynamic trends in key biomasses, stocks and natural capital characterized as “liquidate and crash” or “boom and bust”. In such generalized systems key resources and forms of environmental capacity are exploited totally, or much faster than regeneration rates, and the system based on those resources collapses in concert with its environmental basis. Analogs of this dynamic pattern can be seen in non-human populations that crash when food supplies run out or carrying capacity is exceeded, and human civilizations that crash for similar reasons. The antidote or short-term solution in such cases is often the substitution of a new form of environmental capacity that then enables a newly founded system to arise and the cycle to repeat. The second general dynamic behavior type, one hypothesized to be regularly and causally associated with the Type III highly recycling and renewable ecosystem, could be called “overshoot with net gain” in reference to key stocks and environmental capacity. The main example for this dynamic pattern is forest succession in which biomass reaches a maximum and then declines from that peak toward a lower plateau value of relatively high and stable resources. After successional overshoot, forests are regularly known to self-perpetuate and build and enhance key capacities like soils over periods of 10,000 years (Baisden and Amundson 2003).

By testing for the hypothesized strong and repeatable connections between ecosystem and network organization and dynamic behavior over time – hopefully beyond correlation to build evidence for causal relationships – the ultimate intention was to help advance sustainability science by demonstrating the necessary and sufficient organizing principles for environmental sustainability. If robust, these generic principles ought to be applicable to human-environmental systems thus providing a basis for long-term solutions of such chronic and systemic problems as excess nitrogen loading to the Chesapeake Bay, excess CO_2 emissions to the atmosphere and excess exploitation of non-renewable fossil fuels without compensating replacement energy capacity. The dynamic system types were not yet developed, and thus this full characterization will have to wait for future work. But this project did provide insights into the ecosystem and network typology scheme and its potential to inform sustainability science.

After constructing the dataset for a small sub-network within the U.S. human food web, and after comparison of eight major types of network properties, this case of a human ecosystem network is most similar to the hybrid Type II ecosystem of Allenby and Richards (1994). Looking within the twelve compartment network (Figure 4.1 and Appendix A) one could say that the more heavily agricultural portion of the beef supply network from soils through feedlots is closer to a Type III high-recycling ecosystem, while the more heavily industrial and commercial portion from slaughter and meatpacking through wastewater treatment is closer to the Type I industrial ecosystem. Taken as a whole, this example of the human ecosystem is intermediate and displays aspects of both extremal ecosystem types. 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 that 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 ten 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). This ratio is similar to the estimate that 5 times more grain is needed to feed a person via grain-based versus meat-based diets (Millstone and Lang 2003). 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), in their classic paper, also found that the energy input per calorie of food energy output increased from about 1 to about 10 between 1910 and 1970.

This project also resulted in construction of a dataset for N stocks and fluxes of the human-beef supply chain in the U.S. as scaled to the population of Allegany County, Maryland and as fitting county population and national agricultural statistics for 2005. During this process several important issues were encountered that may prove valuable for future work to extend ecological network analysis (ENA) to human systems. 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, J. unpublished data, Ulanowicz 1986).

ENA requires 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. That is, one can reasonably assume that the quantities of crucial standing stocks and biomasses, for example, which make continued ecosystem production possible, will be maintained over time. If anything, when healthy and developing, natural ecosystems tend to increase key forms of standing stock and productive capacity such as energy capture via primary production, population and biomass numbers for successful species, and quantity and quality of soils. Living systems do not decrease or degrade their primary source of energy – solar energy – as this energy is given off “freely” (as defined next) via physical processes of the sun. Use of solar energy does not involve extraction or exploitation that depletes its capacity as a resource – the act of capturing more sunlight does not cause decrease of the sun’s total capacity proportional to solar energy harnessing; its use (or demand) and provision (or supply) are essentially independent and partly due to this solar energy is often classified as a renewable resource. Thus the steady state assumption for natural living ecosystems can be made for the short-term and can be extended into the long-term. While species turn over, biomasses increase and decrease, soils erode and many other factors change dramatically, no fundamental basis or capacity for the operation of living ecosystems and the regeneration of essential stocks changes unless we extend to perhaps time spans of billions of years.

This same assumption of steady state conditions prior to network analysis 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. That is, the act of using the energy source *does* cause a decrease in that energy source's total remaining capacity. Fossil fuel energy use and provision, demand and supply, are essentially co-dependent and such energy is often classified as a non-renewable resource. Given still large global supplies of oil, coal, natural gas and uranium, the steady state assumption for a human industrial network can be made for the short-term, one or a few years, but it cannot continue to be valid as extended into the long-term. 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 time domain of applicability for steady state ENA to natural systems that extends billions of years into the future, we have perhaps on the order of one to ten 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. Four other factors encountered that would improve the human network dataset include 1) a means to integrate influences of economic network structures and dynamics, 2) simultaneous and integrated treatment of other key environmental network currencies such as carbon and energy, 3) explicit treatment of the stocks, fluxes and cycles associated with human workers as living and ecological actors integral to all the agricultural, industrial and commercial compartments, and 4) further scrutiny of the extension of ENA to industrial entities for which direct comparisons of ecological trophic levels and efficiencies to industrial transfer levels and efficiencies are tenuous, and the designation of industrial compartments as either living or non-living is ambiguous and problematic.

Returning to the steady state assumption, one possible option for incorporating this real issue would be to add a fictitious compartment to the network that accounts for the real decline in non-renewable fossil fuel capacity occurring and balances that depletion with a renewal of lost capacity via hypothetical creation of new renewable energy capacity. The amount of capacity lost during the time span of the network analysis would be recorded in this fictional compartment, and while not actually replenished in the real system this modified ENA method would serve to quantify the debt in “natural capital” or real environmental capacity for operation accrued during the period of study of industrial human systems.

This replacement of lost fossil fuel capacity with renewable energy capacity plays a key part in the input-output rules of Herman Daly (1990, Goodland and Daly 1996), perhaps the most robust and parsimonious operational definition of environmental sustainability available. These principles (listed in the introduction) address relative rates of resource use and waste emission and require that these be within the limits of real environmental systems on which human society is largely dependent. The present study provides evidence that the Chesapeake Bay and Florida Everglades ecosystems meet the Daly rules and are sustainable while the humans-beef supply network violates the rules and is unsustainable. Part of the evidence came from the process of constructing the dataset and the experience of considering the assumptions required for network analysis, namely the assumption of steady state conditions. As discussed above, the assumption is reasonable for the non-human ecosystems over both short and long-terms, but is not reasonable for the human ecosystem over the long-term. Other evidence for this conclusion comes from observed differences in ascendency to capacity ratio, highest effective trophic level, total dependency coefficients and other factors discussed below for which the human network differed from all non-human networks compared.

But first, an example of a test that failed to support this view that human networks are qualitatively different than, and thus less environmentally sustainable than, natural ecosystems. One 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). Based on general understanding of differences between human and natural systems, I expected that industrial human ecosystem networks like that for N stocks and fluxes in the beef supply chain would exhibit greater than 4.5 roles and thus would 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. The WOV is bounded by a minimum of 2 and maximum of 4.5 network roles, and a minimum of 1 and a maximum of 3.1 effective connections per node (Zorach and Ulanowicz 2003)

Contrary to the hypothesis, and like all other systems analyzed thus far, 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, which each had about 4.2 roles, and more than the aggregated Chesapeake Bay and Florida Everglades C networks, which had 2.7 and 3.1 network roles respectively. I made the original hypothesis based on the linked prediction that trophic levels would be abnormally high for human food webs and the false 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, 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 several future questions. First, it bears further study to determine if the limit of 4-5 trophic levels is a solid rule and defining feature of natural food webs in its own right (i.e. independent of the limit of 4.5 roles associated with the WOV). Other workers in network analysis such as Patten et al. (1990) do not agree that trophic levels are limited in such a way, as their methods account for material cycling differently and can lead to very high numbers of trophic levels. The results also call into question whether the much higher number of trophic levels for the example human sub-network studied has much relevance for environmental sustainability. Fowler and Hobbs (2003) have shown that humans fall outside the normal range of variation (outside the 90% confidence level) compared to all other species' distributions of population size, energy use, biomass consumption, geographic range and CO_2 production. They infer from these comparisons that we are possibly ecological as well as statistical outliers and that these deviations can inform how we alter human systems to be more sustainable.

Other major network comparisons results include a greater ascendancy to capacity ratio for humans-beef network than any non-human network. This result could be generalized to an observation that this example 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 to 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). As mentioned in the results 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, as also mentioned, the validity of comparisons of such industrial transfer and true trophic efficiencies requires further examination.

The evidence of 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. Lower residence times observed in the industrial compartments relative to the agricultural and ecological compartments are suggestive as well. Comparisons of total network dependency coefficients – the fraction of total intake by a focal species (e.g., humans) that is mediated by other network compartments over all direct and indirect pathways – 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) for dietary protein supply 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 as depicted for the case of beef. One can test for general plausibility of these results by asking what would happen if any one of these units (e.g., transportation, retail, refrigeration and cooking) in one's personal food supply ceased to operate or perform its role in the supply chain.

Three measures of network connectance were found to be lower for the humans-beef network than any non-human network compared. 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 via which dead human bodies or human wastes were ingested by other species. Seeing the list of compartments that receive the bodies and wastes of the fish, bear, panther and alligator species made me aware that we humans don’t typically consider how we will feed others, how we can in fact become food for other species. The fact figures in Shakespeare’s Hamlet, in which this character says (Eliot 1914):

> We fat all creatures else to fat us, and we fat ourselves for maggots. Your fat king and your lean beggar is but variable service, two dishes, but to one table; that’s the end.

And soon after:

> A man may fish with the worm that hath eat of a king, and eat of the fish that hath fed of that worm…to show you how a king may go a progress through the guts of a beggar.

In the contribution coefficients for black bears, Florida panthers and alligators we see the shared set of compartments and processes, as well as the similar guild of carrion eaters and decomposers, able to fill in details of the ecological actors in Hamlet's scenario for wild creatures if not for humans.

The half of the human N flux treated as an export to the atmosphere via cremation could perhaps be traced forward into other identifiable species and compartments such as locally abundant plants and soils receiving atmospheric deposition of N. And N in biosolids from wastewater treatment plants is being applied to agricultural, forested and restoration lands though it was not quantified for this study. Given widespread practices such as embalming and enclosure in plastic burial cases, it is questionable whether, or over what time frame, the portion of N in human bodies buried in cemeteries is available for decomposition and incorporation into soils and soil organisms. These considerations, while perhaps morbid or uncomfortable, could have deeper meaning as well as additional means of analysis via ENA. One ENA tool not used in the present study quantifies the net impacts between any two species or compartments after accounting for both positive (gains accrued by the one who eats) and negative (losses suffered by the one who is eaten) trophic effects. A software module, IMPACTS, for these calculations is available in both Netwrk 2.0 (Ulanowicz 2002b) and EcoNetwrk (EcoNetwrk 2007). It would be interesting to see if in human food webs the adage holds that, as observed in all non-human food webs thus far, "everything is connected to everything". This property is shown in the matrix of total impacts, which generally has no non-zero elements (R. Ulanowicz, personal communication). Thus all species and compartments do in fact connect to and impact all others, either directly or indirectly, in natural ecosystems. But this would be true for humans and human ecosystems only if we can trace C, N and energy fluxes outward and forward into living compartments able to ingest and benefit from human deaths and wastes.

Several other ideas and issues arose during the project that were not pursued. Some of these relate to the repeatedly observed log-log scaling relations of compartmental stocks and throughputs. While such power law relations have been widely studied for body mass and respiration relations on organismal and species basis (e.g., West et al. 1997), ecosystem scaling relations have received less examination (Ulanowicz and Wolff 1991). Flatter slopes and smaller scaling exponents of the humans-beef system relative to non-human networks suggest possible differences in the meaning of "economies of scale" in human versus natural systems. To the degree that we know natural ecosystems can self-sustain basic operations over many millennia, while also utilizing mainly renewable energy and achieving high material recycling, the stock-flux scaling relationships they exhibit could help inform design of sustainable human ecosystems. The continued observation of stock-flux power law distributions may even suggest a convention to consider these as a priori distributions, which could alter network indices and the information theory formulas used in their calculation.

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 to 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 the methods, 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.

Ideally network modification experiments could be done to show how sub-systems like the humans-beef supply network could be redesigned to be more sustainable. Or conversely, one could alter non-human networks to show how localized changes result in different whole-system indices, patterns or behaviors. Work by Fath and Patten (1998) suggests essentially that overall synergism (similar to mutualism) among species or compartments is guaranteed in all networks when one accounts for all direct and indirect effects. They report that network synergism appears due to three properties common to all networks: indirectness, openness and symmetry. Their work raises the question of whether or how one could design a network without network synergism, or a network with an alternate general intercompartmental relationship such as “network antagonism”. Linking these systemic relations to sustainability could be useful for understanding the importance of whole-system organization on time dynamics and the ability to sustain key forms of natural capital.

Even though not directly quantified, the influence of economics was apparent in some of the properties in the human network and some of the differences relative to natural systems. The high transfer efficiencies, low residence times, low connectance and large inputs of industrially produced N fertilizer all imply the drive to reduce costs and increase production and sales. While these factors that serve to increase efficiency and throughput can be positive, they can also lead to other harmful side-effects if emphasized to the extremes or treated as the single basis for valuation used to guide network growth and development. Ideally, economic and environment networks could be integrated to reward the preservation and enhancement of natural capital as being of equal value to human or financial capital. Daly (1990) is exceptionally helpful and clear on defining capital in general and demonstrates convincingly that human and natural capital are complementary (both are required) rather than substitutable.

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 humans as compared with Chesapeake Bay and Florida Everglades ecosystems. Efforts to increase the speed and efficiency of animal feeding operations - that have resulted in high-density feedlots and switched feed from grass and hay to corn – have also created new problems in waste disposal, animal health, antibiotics use, beef quality and fat content, and human and environmental health. 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.

Chapter 5

Toward a Theory of Applied Environmental Theory

Introduction

The research projects of this dissertation began in 2004, but the ideas behind them began many years prior to the actual start of research design and data collection. One genesis for the work was a kind of epiphany or “eureka!” moment experienced by the author in 1996 near the end of masters degree research on agricultural soils, nematode communities and indicators of ecological health. That flash of seemingly profound insight entailed “seeing” in graphical form a solution to the central problem of the environmental degradation of conventional agriculture and modern culture that also simultaneously appeared to fit like a missing puzzle piece to help solve the persistent quest to understand the origin of life as emerging from a non-living environment. In later years, the two halves of this epiphany were used jokingly to describe the author’s PhD research as addressing just two questions: “What is the meaning of life?” And, “How to save the world?” The jest continued that the special intuitive simplifying assumption that would enable one to study two such deep problems in the space of a four year degree was the idea these two questions share a single answer.

The graphical pattern envisioned to fit both the origin of life and the human sustainability problems was a sideways figure 8. This emerged from two sketched diagrams. One picture portrayed conventional agriculture coupled to human society in a linear pattern with flow-through of matter and energy like an assembly line, or like a figure 8 cut and unfolded into a straight line. This system diagram had boxes and arrows for various stocks and fluxes of matter and it seemed to explain the environmental problems of our existing circumstances in the way wastes necessarily (by system design and configuration) poured out the end of the line into landfills, oceans and atmosphere. The second picture represented a hypothetical two-cycle system of agriculture-and-society in which most material leaving as waste after its circulation through human society was recycled as resource inputs needed for the next cycle of food and fiber production. This seemingly solved the “fouling our own nest” problem above on paper. And, as sustainability expert, William McDonough, has stated in many public lectures, it seemed a simple system design with the power to “eliminate the concept of waste”.

The latter diagram looked like a figure 8 on its side, and in two instant mental hops this evocative image linked to the infinity symbol and then to an ecological topology of flow, transformation and relationship potentially capable of bridging inanimate energy and matter with the open-ended and ideally infinite future of life as a unique process in the universe. The dynamic image of the Möbius strip may have also catalyzed this experience, as drawn with ants traversing it endlessly by M.C. Esher. Other Escher works like Drawing Hands, Whirlpools, Ascending and Descending likely helped as well. C.S. Holling’s sideways figure 8 depicting the recurring cycle of ecosystem growth, disturbance, release and renewal and the two-cycle and binary complementarity symbol of the yin yang also played assisting roles.

Some of this story and the attendant corroborating literature and logic were reported in the Bulletin of the Ecological Society of America (Fiscus 2001-2002). Inspired by this idea and with great hopes for its potential to help solve major real and theoretical problems, the author wrote and emailed leading thinkers in ecology, Gaia theory and complexity theory and asked for their opinions and critique. Replies from

James Lovelock, Lynn Margulis, John Holland, Fritjof Capra, Stuart Kauffman, Simon Levin, Pat Kangas, Bob Ulanowicz and others. Margulis, Holland and Kauffman all suggested that I contact Harold Morowitz. This advice was followed, and he was so kind and generous as to invite the author to George Mason University for lunch and a long discussion. Dr. Morowitz agreed that material recycling would be of great adaptive benefit as soon as it arose, but he disagreed with the idea of an ecological material cycling system as likely prior to or able to generate life in its cellular and organismic form. Pat Kangas provided a citation to work by Howard Odum (1971) in which Odum had diagrammed the same basic idea of an ecological origin of life with recycling aided by abiotic hydrodynamics in the form of “circulating seas”. James Lovelock said he liked the idea, but the scenario needed some role for the environment to play. Bob Ulanowicz was very optimistic and supportive, shared the basic view and added insights to it, thought a PhD would help with pursuit of such ideas, and agreed to serve as the author’s PhD co-advisor.

Development of the theoretical ideas proceeded for some time. The two mutually causal life sub-systems were characterized as proto-autotrophic and proto-heterotrophic functions, and, borrowing from Lotka’s (1925) phrase “coupled transformers”, the synergistic team was described as a unitary whole made of “coupled complementary processes”. These two sub-functions were further interpreted as a molecular string “composer”-with-“decomposer” system plausibly representing the basic functions shared by both metabolic and genetic systems of cells. Links were made to potential abiotic pre-cursors to this two-phase and perpetually cycling system in 1) the hydrological cycle, alternating between liquid and gas water phases via evaporation and condensation, 2) the erosion and deposition cycle, by which sediments move from land down toward oceans and for which the cycle can be reversed by uplift and new mountain formation, and 3) the unique estuarine turbidity maximum zone near the head of tide in estuaries, where the annual cycle of freshwater runoff meets the monthly and other cycles of ocean tides forming a natural churning washing machine-like action with resuspension of sediments and other features akin to Odum's (1971) "circulating seas" origin of life scenario.

This model of life also continued to appear fully applicable to present day sustainability challenges and capable of solving major human environmental problems. If one accepted the fundamental unity and requirement for the two complementary modes for lifelike open-ended evolution and environment-enhancing operation, then one could apply this first principle in the design and actualization of any human production, technological, agricultural, economic or development project. Following the model of autotrophy-with-heterotrophy, composer-with-decomposer one could design and build any material construction process in concert with a coupled complementary material deconstruction process. Then one could grow and expand these two sub-functions as matched in spatial and temporal scales. Ideally such an ecological basis for the creation of human artifacts would enable them to have the best lifelike properties, to "take on a life of their own", to eliminate the concept of waste and solve any pollution problem before it even arose.

But after further attempts to pursue this idea and its implications directly, the research was hindered partly due to a lack of compatibility with the goals, values and ways of the author's highly applied research institution. Conceptual trouble also arose with practical means of development and testing of such a general idea, then called "the ecosystemic life hypothesis”. A change of course was made to seek aspects of this holistic view of the essentially cyclic and community-ecosystem-based aspect of life relevant to pressing environmental problems like those of the Chesapeake Bay. It seemed that if the idea were valid and useful, it ought to provide pragmatic information able to guide research into ecosystem dynamics of excess nitrogen loading from landscapes to surface waters and other similar projects being studied at the Appalachian Laboratory.

The gist of the ecosystemic life hypothesis applied to human-environment problems and environmental sustainability is that ecological relationships are critical to both understanding how living systems work and to designing and implementing human systems that can be free of major chronic and systemic problems like excess CO_2 emissions, excess N loading to surface waters and others. Three research projects intended to explore and test this simple but profound general hypothesis developed and conducted. Some of the major results and experiences from those projects are summarized next. Following the project-specific synopses the mutual meaning and implications of the projects is presented. Finally the collective take home messages are applied to identify warranted and likely beneficial changes in theory - philosophy, science paradigm and cultural mental models - and action – principles and programs for restoration of environmental quality and actualization of environmental sustainability. All of these revolve around values that operate for the author in varying degrees of explicit, conscious and overt versus implicit, subconscious and covert ways. A way to summarize the core of these values is akin to those self-evident truths listed in the U.S. Declaration of Independence - the rights to life, liberty and the pursuit of happiness. Based on a personal view that liberty (largely for an elite few) has been over-emphasized to the detriment of life and happiness (for the many) since these historic words were written, the summary seeks to re-balance these and focuses more on life and happiness as fundamental truths, both of which are amenable to scientific inquiry and exploration, as well as inalienable human rights.

Summaries of Three Research Projects

The Signature of Synergy in Soils

The first attempt to apply the ecosystemic life hypothesis and kindred holistic ecological concepts involved a comparative ecosystem study of soils (Fiscus 2007a in preparation). Prior research experience (Eshleman et al. 2004, Eshleman et al. 2001) and work of Eshleman (2000) had shown that forested watershed ecosystems located on different bedrock geologies responded differently to extreme natural disturbance events of heavy defoliation by gypsy moth caterpillars. In addition to differences in geology, we had basic information that soils and vegetation also differed for the many defoliated watersheds studied in Virginia, Maryland, Pennsylania and other nearby states.

Eshleman’s important results came partly from what he has called “serendipity”, by which he seemed to mean he just happened to be in the right place, at the right time, measuring the right things. He and colleagues at the University of Virginia had maintained long-term monitoring on a group of mountain streams in Shenandoah National Park. They thus had baseline data for stream water constituents like nitrate for many years, when in the late 1980’s the wave of the non-native gypsy moth’s southward migration swept over these watersheds. Within one to three years after heavy and sometimes complete defoliation, nitrate concentrations in these streams spiked up with 10 to 100 fold increases. Nitrate export then declined in all watersheds and within 10-15 years had returned to the very low baseline export rates they had seen prior to disturbance.

From learning about both the very low baseline nitrate export rates and the resilience and recovery of this high N retention after severe disturbance, forested watersheds were seen as amazing example systems with potentially great lessons to teach us. In short, forests simply do not exhibit the excess N loading and water quality problems that the Chesapeake Bay and its landscape watershed have. For some watersheds, like the Patuxent River, while some improvements and reductions in N loading had been achieved, it was widely known that these improvements had seemingly stalled. After about 10 years of good reductions, N export in the Patuxent had reached a plateau around the year 1995 as if current management practices had “picked the low-hanging fruit” and then succumbed to diminishing returns from a partial management solution. Defoliated forests on the other hand showed essentially complete recovery to pre-disturbance low N export conditions. And the baseline N concentrations in forested watershed streams were about 40 times lower than those for the heavily developed Patuxent watershed.

A general hypothesis was conceived that soils and organic matter played important roles in the ability of forests to both retain nitrogen under normal conditions and recover that N retention capacity after disturbance. To begin to explore the role of soils, the first project studied soil structure and changes due to land use. Old growth forests (150-300 years old), middle-aged forests (80-180 years old) and long-term agricultural sites (farmed for 60-100 years) in the Fifteen Mile Creek watershed and nearby area of Eastern Allegany County in Maryland were sampled. All sites were on the same soil type, Calvin shaly silt loam. Samples were taken at multiple depths in the vertical profiles of soils and data gathered for bulk density, total nitrogen, total carbon and organic matter contents. Two soil cores were taken on each of three plots on each of the three land use types for a total of 18 cores. Laboratory analyses for C, N and organic matter content were performed at Appalachian Laboratory with great assistance by many faculty, staff and fellow students.

The data showed consistently greater total C storage in both forest types relative to the agriculture sites. Total N storage was similar across all three site types. Soil C, N and organic matter all fit power law depth distributions, except for C distributions in some of the agriculture sites with greatly reduced C and organic matter in the surface layer. For these anomalous sites the depth profiles fit an exponential depth distribution better.

The power law depth distributions were a surprise and had not been predicted, but a very welcome surprise as at the time power laws were a hot topic related to complexity, self-organization and spatial patterns of chlorophyll, salinity and temperature on the surface of the Chesapeake Bay (Gardner et al. 2003). In this chapter for the soils study, an explanation was posed for the power law depth distributions of C, N and organic matter (OM) using a concept from Schneider (2001). He wrote that power law distributions can be generated by two opposing forces operating at exponential rates of the same order of magnitude (e.g., birth and mortality). This interplay of two antagonistic forces is echoed in the dialectical and two-tendency nature of ecosystems and the universe characterized by Ulanowicz (1997). To the author's knowledge, the generation of the vertical structure of soils has not been explained in such a systemic way. Further research, such as using a model for forest soils based on two opposing exponential rates to see if they can generate power law depth distributions, could be fruitful.

The paper that inspired the title of this chapter was, "The distribution of soil nutrients with depth: global patterns and the imprint of plants" (Jobbagy and Jackson 2001). Their paper and title implied that the vertical distribution of soil nutrients is explainable by the action of plants to draw up nutrients via roots and deposit them on the surface via litter fall. The term "synergy" in the title chosen for this first study aimed to suggest that the pattern of high concentrations of limiting and valuable nutrients near the surface is better understood as the result of multiple players in a community as linked via cyclic processes and relationships. The minimal complement to form a community is two, and thus the two major ecological roles of autotrophy and heterotrophy seemed the minimum functions necessary to account for the creation of a strong and functional gradient in soil storage of C, N and organic matter. That these two functional types work largely in opposite directions with regard to autotrophic inputs and heterotrophic outputs of C ties the power laws in to this view that ecosystemic organization and interdependent functional relations are likely at play, integral in their own right and not reducible to epi-phenomena of the actions of organisms, species or single functional types.

One other basic but important sense from this research is that forestry appears essentially sustainable with the long-term rotations done in Green Ridge State Forest where several of the forest plots were. Cutting timber every 80 years or so seems compatible with continued soil generation, maintenance of power law depth distributions in C, N and organic matter, and a thick and rich layer of litter and organic matter on the surface. In contrast, agriculture as practiced on the other sites, likely including annual or regular tillage and net loss of vegetative matter via crop removal, seems unsustainable. This land use practice depletes soil C and organic matter, removes the black litter and organic surface layer and alters the strong gradient of concentrations across the vertical profile.

Self-examination of Environmental Science as an Environmental Process

A second research project focused on a very different issue, yet in certain fundamental ways continued the thread of the ecosystemic life hypothesis. This project was conceived partly based on a sense that the traditional emphasis on objectivity in environmental science could be a limitation in efforts to understand and solve environmental problems. This hunch involved the simple observations that 1) the major environmental problems are caused by humans, 2) we environmental scientists are humans, and 3) we environmental scientists in academic, research and government agencies appear to be living and working in the same lifestyle, technological, economic and cultural systems that are responsible for chronic and systemic environmental problems like those with CO_2, N, energy and others. From these self-critical starting points, a goal was set to examine whether the Appalachian Laboratory, as a typical environmental science research organization representative of mainstream science, could best be considered to be “inside” or “outside” the natural system context as defined by major C, N, energy and water-related environmental problems. Another goal was to assess whether the operations of the Appalachian Lab (AL) are environmentally sustainable or not. The basis for this test was the set of Daly input-output rules for environmental sustainability (Daly 1990, Goodland and Daly 1996).

Audits of the annual AL uses of energy and water and emissions of C and N from 1999-2005 were conducted. These fluxes were compared to estimated C and N absorbance capacities of typical local hardwood forests as comparative ecosystem reference basis and for testing for sustainability – the Daly rules require waste emissions within the capacity of the local environment to absorb without reduction in future waste absorption capacity. The renewable local water supply from precipitation and renewable local energy sources from onsite solar radiation and wind energy available on nearby ridge tops were also quantified.

Results showed that the operations of AL cause emissions of 70 times more C and 60 times more N than can be absorbed by local forests. This chapter concluded that AL is environmentally unsustainable based on C and N emissions. Energy use was found to come from 99% non-renewable sources, and since AL does not allocate any resources toward development of equivalent renewable energy capacity (another Daly rule), the conclusion was again made that AL is unsustainable based on energy use. Water use for the lab was far less than ambient rainfall and was deemed sustainable. Solar energy was estimated as sufficient to power the lab if the roof were covered with solar panels (but this simple comparison neglects important economic and feasibility issues).

These results were also used to infer that the environmental scientists at AL, and the organization as a whole (of which the author is part), is an active participant and active causal agent of the problems of excess CO_2 emissions and excess N emissions. Both of these human excesses harm the Chesapeake Bay. Geographically and spatially, the lab is located near the farthest upstream headwaters, in the small Sand Spring Run watershed, a tributary to George’s Creek, which flows to the Potomac River and on to the Bay. The “self-examination of environmental science” project suggests that not only are we inside the watershed of the Bay, but we are also inside any system boundary one could draw to the fully characterize and study the causes of the Bay’s problems and attempt to find solutions.

This paper ended with the suggestion that there is a systemic cultural aspect to the environmental problems of the Chesapeake Bay, the U.S. and the world. Hoping to frame this as good news, the results were posed as a rare gift of direct access to knowledge of the nature of this cause, as we are immersed and participating in it ourselves. Going further, one could characterize a collective cultural myth, a shared value system or a consensus reality based on *subordination of environmental value to other values* as the ultimate cause of our chronic and systemic environmental problems. In environmental science we are accustomed to examining and criticizing agriculture, transportation, industry, development, energy, government and other sectors for their failure to achieve, maintain or restore environmental quality. And we are familiar with justifications that profit, progress, food production, practicality, politics and other values can at times be priorities that trump environmental quality as a value. But this audit provides evidence that we do the same thing ourselves – it is just that the values we elevate above maintenance of environmental quality and capacity related to C, N and energy are scientific, educational and associated personal and socioeconomic values.

A focus on the silver lining of this critique could lead to long-term benefits for both environmental science and society. If we begin to account for those resources integral to the *environmental capacity to do science*, this can ensure that we continue to be able to do environmental science and are able to pass on this important field to future generations. If we have to fit our organizational behaviors to the real carrying capacity limits of each local environment, that would seem an excellent opportunity and impetus to learn about our ecosystems in even more intimate and accurate detail. Such research could provide meaningful experiences for students as well as help us reduce the amount of taxpayer money we spend.

In terms of science paradigm advances, this self-examination could also contribute to efforts to develop the internalism perspective. Salthe (2007) describes internalism:

> This is a newly emerging point of view in science, with few antecedents, which include phenomenology, the thinking of J.J. von Uexküll, and the autopoiesis model of Maturana and Varela. Current major thinkers include Koichiro Matsuno, Yukio-Pegio Gunji, Otto Roessler and George Kampis. My own perspective on this is that internalism becomes necessary if we try to make a science which begins with the fact that we are inside, as participants in, the universe that we are studying. Internalism applies to such advanced technological situations as cosmological knowledge in the face of the finite speed of light (we cannot get outside the universe, or see it whole) and operationalism, as well as to the situation of a newborn infant trying to manage in the world. Internalism is a viewpoint that accepts in advance limits to knowledge, and any viewpoint expressing limitations, like Herbert Simon's "bounded rationality" is internalist. The problem of waste disposal is an important currently visible internalist predicament.

The implications are potentially revolutionary and may lead to a “new kind of science” as we begin to internalize the environmental costs of conducting science. Leaders in the emerging field of sustainability science affirm that sustainability entails fundamental change for science. Kates et al. (2001) stated, “the structure, methods and content of the scientific enterprise would have to change in order to pursue sustainability science adequately.” Central to these changes may be new forms of environmentally self-reflexive accounting for progress, reward and advancement structures and strategic plans for conversion of science operations to meet the Daly input-output rules for environmental sustainability as tied to real local environmental contexts. Perhaps we can gain insights and cooperation as the U.S. culture and economy as a whole (hopefully) work on the same program. Or perhaps we in environmental science can help to lead the way.

Comparative Network Analysis Toward Characterization of the Necessary and Sufficient Organizational Criteria for Environmental Sustainability

The third and final major research project of this dissertation again used comparative ecosystem studies to search for ecosystemic root causes and solutions to major environmental problems facing citizens of the Chesapeake region and humanity as a whole. The original research plan was to construct datasets for and compare three ecosystem networks, tracing C, N and energy, for developed, agricultural and forested watersheds. As the project progressed, the watershed approach was largely abandoned and the ecosystem currencies were reduced to two. New data collection focused on N in the beef supply subset of the U.S. human food web. The last vestige of the watershed approach that survived was characterizing N fluxes into and out of the main wastewater treatment plant for Allegany County and Cumberland, Maryland. This plant delivers its effluent to the Potomac River. Instead of a new dataset for a forest ecosystem network, four existing datasets were used for testing as natural and sustainable reference ecosystems. These were C and N networks for the full Chesapeake Bay mesohaline ecosystem, one aggregated dataset for the Chesapeake Bay C network, and a C network for a cypress swamp ecosystem of the Florida Everglades.

The Daly (1990) input-output rules for sustainability were again employed to define and test for environmental sustainability. In addition an ecosystem typology (Allenby and Richards 1994) was explored for its utility in defining fundamentally different ecosystem types and for differentiating between human and non-human forms of ecosystem network organization.

The hypothesis that a human ecosystem network would exhibit a number of network roles and effective connections per node such that it plotted outside the “window of vitality” (Ulanowicz 2002) was not supported by the results. Instead, the N network for the humans-beef supply chain plotted inside the window of vitality like all other ecosystems studied thus far. The hypothesis that the human network would be most like the Allenby and Richards (1994) Type I heavily industrial ecosystem was not supported either. Instead, the N network of the humans-beef supply chain was more of a hybrid Type II ecosystem intermediate between a maximally polluting industrial ecosystem and an ideally recycling Type III ecosystem with natural analogues like forests.

Several interesting results did suggest major differences between the human sub-network studied and all natural ecosystems. The ascendency to capacity ratio was greater than 50% for the beef supply chain and 43% or less for all non-human food webs. The highest effective trophic level was 8.1 for the human network, far above the highest in the reference networks, 4.9. Caution was urged in comparing the pseudo-trophic levels of industrial units like slaughter and meatpacking, transportation and retail with true trophic levels in real food webs. Humans were unlike any other species in their total dependency on several compartments in the highly linear beef supply chain with no alternative pathways. The highest effective trophic level also was decoupled from the number network roles, an important learning for the author. This result could potentially aid the effort to find an analytical solution for the fourth edge of the window of vitality, the limit of 4.5 network roles observed in all real networks so far. The other three edges have analytical or intuitive explanations, but this remains a need for the limit of network roles (Bob Ulanowicz, personal communication).

One result evoked spiritual and philosophical overtones. The food web comparison showed no trophic N contributions when tracing forward from humans to other species. Unlike for bluefish, alligators, black bears and Florida panthers, contribution coefficients could not be calculated for N in human deaths and wastes becoming inputs to soils or sediments or food supply for other species. This result would have been somewhat different had the data collection been more comprehensive, but the experience stimulated the awareness that we do not often think about or discuss whom we humans will feed, how we ourselves can emit or be food for other species. Perhaps this point can aid with developing a more internalist ecosystem science. Or perhaps it provides clues to other aspects of the root causes of our systemic cultural environmental problems, such as knowledge, fear and denial of our own mortality or the predominant life science focus on organisms with finite life spans. These are discussed more below but largely left for future inquiries.

The original research proposal was to tie the results of comparative network analysis studies to dynamic behavior and trends in key forms of environmental capacity such as soils, energy, C and N. Based on hypothesized strong, repeatable and even causal links between system (network) organization and dynamic behavior over time the proposal promised contributions toward characterizing the necessary and sufficient organizing principles for environmental sustainability as associated with maintenance of environmental capacity and capital. The dynamic modeling and causal inference portions of this research were not completed, but these could plausibly be done and might yet yield the promised results.

One starting point for completing these tasks could be the diagram in Figure 5.1. This figure follows a similar three compartment autocatalytic network of Ulanowicz (1997) and the inclusion of a compartment for environmental context of Zorach and Ulanowicz (2003). It depicts an autotrophic functional component (A), multiple heterotrophic roles (H_1, H_2, etc.), and environmental context (E). In addition to the loop of positive links depicted in Ulanowicz (1997), the three-part base of this model has a complete set of negative influences and thus two sets of opposite relations, both of which connect around in complete loops or cycles, operating in parallel or simultaneously.

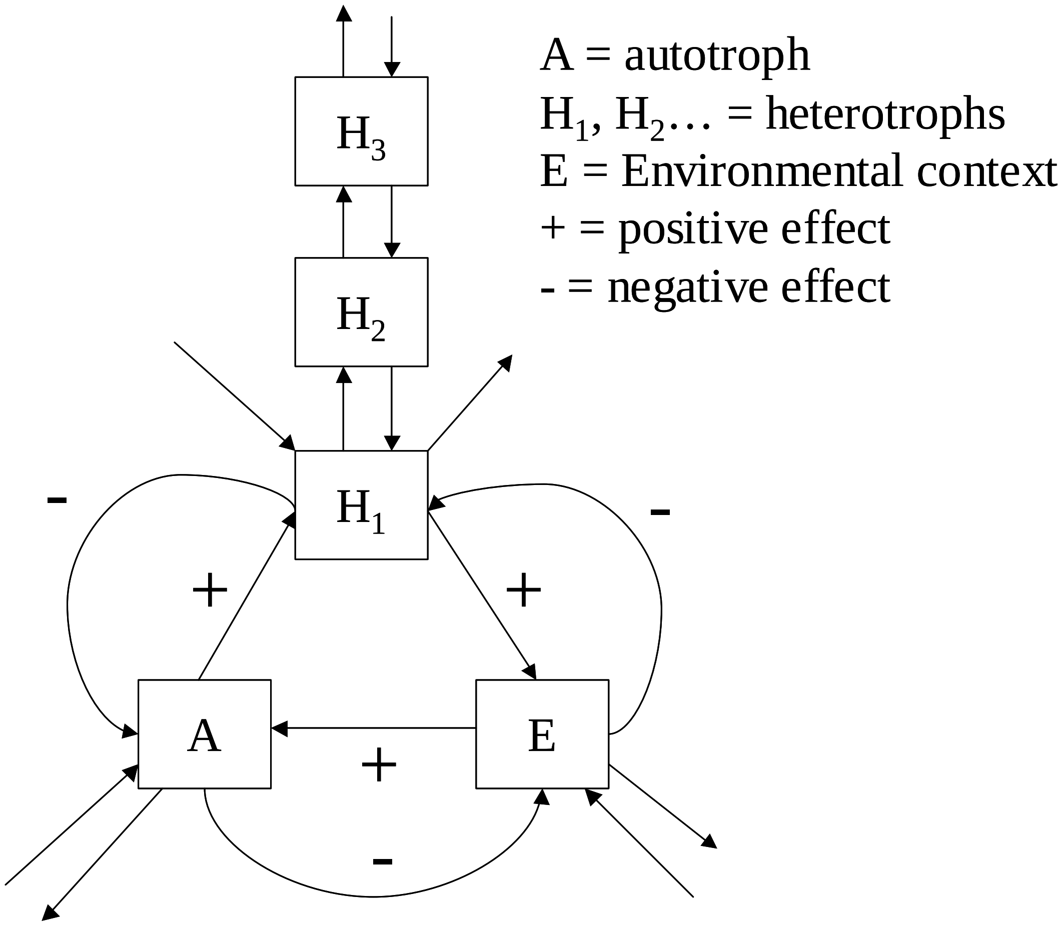


Figure 5.1. Schematic of community/ecosystem as an unfractionable, interdependent whole integrating two biotic functional roles and an abiotic environmental role.

The positive (+) loop can lead to exponential growth, autocatalytic network stimulation, mutualistic growth and development, maximum storage (Fath et al. 2001), and the centripetality (Ulanowicz 1997) that draws in material much like a gravitational action. The negative (-) loop can lead to exponential decrease, antagonistic predation and competition, maximum dissipation (Fath et al. 2001), and perhaps a centrifugal force associated with radiational action to spin outward, spin off new forms (adaptive radiation) and ejection of various energy and material wastes. The two parallel loops – each potentially corresponding to exponential rates of change or flux – could provide the antagonistic combination Schneider (2001) proposes can lead to power law relations. As Fath et al. (2001) showed, these two antagonistic tendencies can be reconciled via the concomitant dynamic principle of increasing residence time for material in the whole network system.

Including the environmental context with an integral role – perhaps as most obvious in the form of soils, sediments, aquatic chemical properties and atmospheric composition – satisfies James Lovelock's suggestion for improving the ecosystemic life hypothesis and provides a basis for exploring how life and environment co-evolve. If this co-evolution is at least a bit more positive than negative, the weights of the + arrows a bit stronger than the – arrows, then one could conceive of environmental sustainability as a mutualistic (+,+) relation between life and environment. It seems this model could benefit from and contribute to efforts in impredicative loop models such as those of Kercel (2003) who has used hypersets, and Giampietro (2004) who calls them "chicken and eggs processes". Both build on works of Rosen (1991).

Finally, this model could provide a better working explanation of the power law relations between body mass and respiration which West et al. (1997) treat as having developed and evolved in plants and animals independently as based on physical constraints on fluid flow and fractal branching network design for organismal circulatory systems. Instead of having evolved independently in plants and animals, such power law distributions of mass-energy or stock-flux relations could have co-evolved interdependently – not only in the whole context of living community action between plants and animals, but also as integrated with environmental and biogeochemical stocks and fluxes such as those in soils, whose C and N depth distributions may hold memory of this complex and unfractionable triadic synergy.

The Collective Meaning of Three Projects

Speaking of triads, to distill the central results and take home messages from these three projects, it may help to invoke an analogy to triangulation as when multiple geographic points of reference are used in orienteering and multiple perspectives are used in social science. For the latter, Wikipedia.org (2007d) stated:

> In the social sciences, triangulation is often used to indicate that more than one method is used in a study with a view to double (or triple) checking results. This is also called "cross examination". The idea is that one can be more confident with a result if different methods lead to the same result.

The three projects summarized here differed in their approach, yet in many ways led to the same result. The relationship of ecosystem organization to environmental sustainability was examined by way of 1) a comparative study of soils in human agricultural versus forested land use types, 2) a comparative study of environmental fluxes of a science research lab versus a local forest, and 3) a comparative study of a partial human food web relative to four aquatic and wetland food web networks. In terms of disciplines or sub-disciplines, these could be described as an ecosystem field and laboratory study, an environmental audit and human ecology study and a network analysis study. In addition to the author and his inherent values and biases, these studies also shared some basic findings.

In all three cases humans exhibited qualitative and systemic differences relative to natural ecosystems. Human-dominated soils showed losses of carbon and surface organic matter whereas forested soils showed maintenance and (by extension forward in time) continued gains in these systemic forms of productive capacity. The case study of the human science enterprise showed C and N emissions far in excess of the capacity of the local environment's waste assimilation capacity. The lab studied also showed near total dependence on non-renewable energy unlike the forest reference system with reliance on renewable energy. And the partial human food web, likely fairly representative of the complex, energy and resource intensive, highly competitive U.S. food system as a whole, showed an unusually high degree of organization and efficiency and lack of redundancy in supply pathways compared to non-human networks.

One way to synthesize these joint results is to say that this "triangulation" of studies suggests:

1. Since systemic differences exist in three such disparate areas as agricultural soils, academic science building operations and industrial food supply chains, and

2. Since these systemic differences are correlated, and perhaps causally linked, with major C, N and energy-related environmental problems, then

3. It is reasonable to characterize a single systemic human environmental problem and infer that, as for the manifest effects, the root cause of this problem is not likely isolated in any one sector. And,

4. Instead, the root cause of all these systemic differences and their associated problems may be some single factor or set of related factors that is diffuse, non-localized, shared across all sectors, or spread throughout the entire culture in which all these activities are embedded.

If one accepts this logic and the joint evidence of the three studies for the moment, then initial trial runs could be conducted to search for this hypothetical single cultural factor or set of factors implicated as the root cause of the systemic and unitary "humans in the environment problem".

Linking back to the prior work on the ecosystemic life hypothesis, it seems this general concept has withstood three tests, may have relevance still, but may also be seen in new light. This hypothesis portrays the original and fundamental nature of life as an ecological or ecosystemic process in which two coupled complementary functional types co-arose, co-create, co-evolve and co-sustain in mutually causal interdependence. This hypothetical proto-ecosystem had a material cycling aspect as integral to its organization from the beginning, and as in Odum's (1971) depiction this crucial material cycle was aided by the "free" environmental subsidy of a hydrodynamic circulatory system. This hypothesis, or Odum's plausibly operational scenario explaining the original and fundamental nature of life, could now be used to suggest that at least one facet of the systemic cultural cause of our human-environment problem is *an incorrect basic metaphor, paradigm or mental model for life*.

In our U.S. culture we now have a dictionary definition of life that equates life with organism (Life, noun. “An organismic state characterized by capacity for metabolism, growth, reaction to stimuli, and reproduction”, Merriam-Webster 2007), a story of the origin of life as the emergence of the first cell (e.g., The Beginnings of Cellular Life, Morowitz 1992), and a theory of evolution in which the focal units of natural selection are organisms, species and genomes. Is it just a coincidence that we in the U.S. also now live and operate in ways that devalue and degrade the ecosystemic and biospheric life support capacities of future generations and jeopardize and limit the future options of other humans and all species?

The alternative is to suggest a causal or influential connection between 1) our basic, shared, collective, scientific and societal understanding of what life is, how it is defined, and how it originated and evolved and 2) what it takes to live well and to live in ways that enhance and sustain rather than degrade and deplete key forms of environmental capacity and quality. This seems more plausible, and it suggests the need for consideration of at least two equally valid and irreducible models, metaphors or paradigms for life.

“Life as organism” can hardly be thrown out totally – it has too much obvious validity, truth, merit and utility for understanding and action. But it may well be necessary to add a second model of “life as community/ecosystem” of *fully equal* validity, truth, merit and utility to the mainstream science view and cultural conventional wisdom of organismic life. “Life as community/ecosystem” serves the need for a continuous view of life that matches the continuous story, evidence and observations of life as persistent over nearly four billion years. Ecosystemic life as an equal mental model for life also provides a foundational counterbalance to the temptation to over-emphasize the importance, primacy and standing of individuals and organisms. If these discrete and single lifespan living entities are the beneficiaries and heroes of the modern celebration of *independence* which the American Revolution has helped to promote, the communities and ecosystems of life are the left out continuous and multi-lifespan entities now awaiting the necessary and emerging *declaration of interdependence* (for the origin and history of this phrase see Greenpeace 2007).

Our culture, our actions, our behaviors and the resulting cumulative effects and manifest problems in widespread, pervasive and worsening environmental degradation all are compatible with a belief and scientific paradigm that life is of, by and for organisms and individuals. It is as if the future or real world on Earth does not exist beyond the horizon of the death of an individual – like some kind of mental, psychic or cultural barrier blocks our view, attention and empathy to the authentic needs, intrinsic value and equal standing of life-the-continuum that extends well after, and far before, our own personal lives and deaths. Darwinian natural selection and its infusion into competitive economics fit this worldview as well.

One example of a new mindset, shared mental model, paradigm shift, or consensus reality that could both fit better with objective reality and help solve our environmental problem comes from Daly and Cobb (1989). They propose that “person in community” is a better mental model than “human as individual” for economic theory and practice. They wrote:

> The view of *Homo economicus* derived from that anthropology [of the 18th century] and still underlying the existing discipline [of economics] is radically individualistic. Society as a whole is viewed as an aggregate of such individuals. We want to replace this with an image of *Homo economicus* as person-in-community.
>
> The individualism of current economic theory is manifest in the purely self-interested behavior it generally assumes. It has no real place for fairness, malevolence, and benevolence, nor for the preservation of human life or any other moral concern. The world that economic theory normally pictures is one in which individuals all seek their own good and are indifferent to the success or failure of other individuals engaged in the same activity. There is no way to conceive of a collective good – only of the possibility that there can be improvement for some without costs to others. Even this theory of social gain is possible only by neglecting relative status along with feelings of good will and ill will. It would be difficult to imagine a more consistent abstraction from the social or communal character of actual human existence!

It seems likely that the foundational principles, consensus beliefs, operational definitions and working assumptions of biological, ecological and environmental sciences, and science as a whole, have some responsibility in the spread and persistence of such monolithically individualistic views as those Daly and Cobb critique in economics.

As an antidote and balancing movement, we could promote the ecological metaphysic of Ulanowicz (1999) and kindred works of other systems ecologists (e.g., Patten in preparation, Fath et al. 2001) who demonstrate convincingly the holistic features of life via the ecosystem network model. The basic ecological principles discovered and defined in these works, if elevated to equal standing with existing organismal and genomic first principles, would serve to reintegrate organisms and individuals with their necessary living community and abiotic environmental contexts. Fixing this unnatural separation in our “group mind” by way of the collective intelligence of science could be an effective first step to understanding the causes of our systemic environmental problems and seeing our ways to their lasting solution. Using these holistic ideas to *think with*, we can go in search of understanding and healing the "human-in-environment" as an inherently relational and ecological being now in trouble and distress.

Philosophical Implications and Recommended Actions – Toward a Theory of Applied Life-Environment Theory

In the spirit of the pragmatic philosophers C.S. Peirce, John Dewey and William James, the ideas and concepts of this work would ideally have some real practical value and application. Without taking pragmatism to utilitarian extremes, the imperative for practical applications for philosophy, ideas and theory is compelling. A popular description of the American-made philosophical pragmatism school says (Osborne 1992):

> While Wild Bill Hickock was roaming the plains, C.S. Peirce was honing his thoughts and in 1878 came up with the following: "Consider what effects, which might conceivably have practical bearings, we conceive the object of our conception to have. Then our conception of these effects is the whole of our conception of the object."
>
> This was simply meant to be a logical maxim for working out the meaning of words and concepts according to their practical significance. Or, in other words, to establish the relationship between thought and action.
>
> Our idea of anything is our idea of its sensible effects. If words mean anything, we should be able to test them. But if words relate to qualities about which we can discover no practical effects, then they are meaningless.
>
> It is astonishing to see how many philosophical disputes collapse into insignificance the moment you subject them to this simple test of tracing a concrete consequence. In fact, almost every proposition of ontological metaphysics is either meaningless gibberish or else downright absurd…
>
> William James summed up the new version [of pragmatism]…"Ideas become true just so far as they help us get into satisfactory relations with other

> parts of our experience. What, in short, is the truth’s cash value in experiential terms? What does it do for you?”

What might one answer if asked after reading this dissertation or a part of it:

> What applicable knowledge did you gain about environmental sustainability?
>
> What will you now do based on this new knowledge?

Did this work suggest other knowledge that you need in order to act for sustainability, perhaps knowledge specific to your real local environment?

For one last round of trying to distill the core concepts, theory or philosophy this work supports and suggests, Arne Naess’s deep ecology and ecological self (1989) provide insight. Naess’s deep ecology is compatible with the ecosystemic life hypothesis (Fiscus 2001-2002), the ecological metaphysic (Ulanowicz 1999) and a holistic mental model of life as extensive in space and continuous in time beyond the body and life span of the organism. He wrote:

> Care flows naturally if the 'self' is widened and deepened so that protection of free Nature is felt and conceived as protection of ourselves.
>
> Just as we need no morals to make us breathe, if your 'self' in the wide sense embraces another being, you need no moral exhortation to show care. You care for yourself without feeling any moral pressure to do it.
>
> If reality is like it is experienced by the ecological self, our behaviour naturally and beautifully follows norms of strict environmental ethics.

Suggesting a “hard” scientific basis for these views – as in proposing the scientific definition, origin theory and evolutionary theory of life all be revised to include a second equally weighted model of “life as community/ecosystem” – could complement the other real evidence, intuitive appeal and ethical strength of Naess’ work.

To link in light-hearted and artistic ways to past great thinkers, one could imagine how history might have unfolded differently – how the real effects of different ideas would have manifested differently - if Leonardo DaVinci had made a different image and Rene Descartes had transcribed a different seminal thought. Instead of the famous "Leonardo Man", depicting a human – individual, organism – in isolation, what if this quintessential Renaissance Man, the world famous artist-scientist, had created an image of the "Leonardo Living Couple", as in Figure 5.2? (Image courtesy of Steven Fiscus.) How might a different conception of ourselves as living in a community context, and a symbolic emphasis on the necessary life relation to our "better half", the plants, led to a different world environmental situation than we now face?

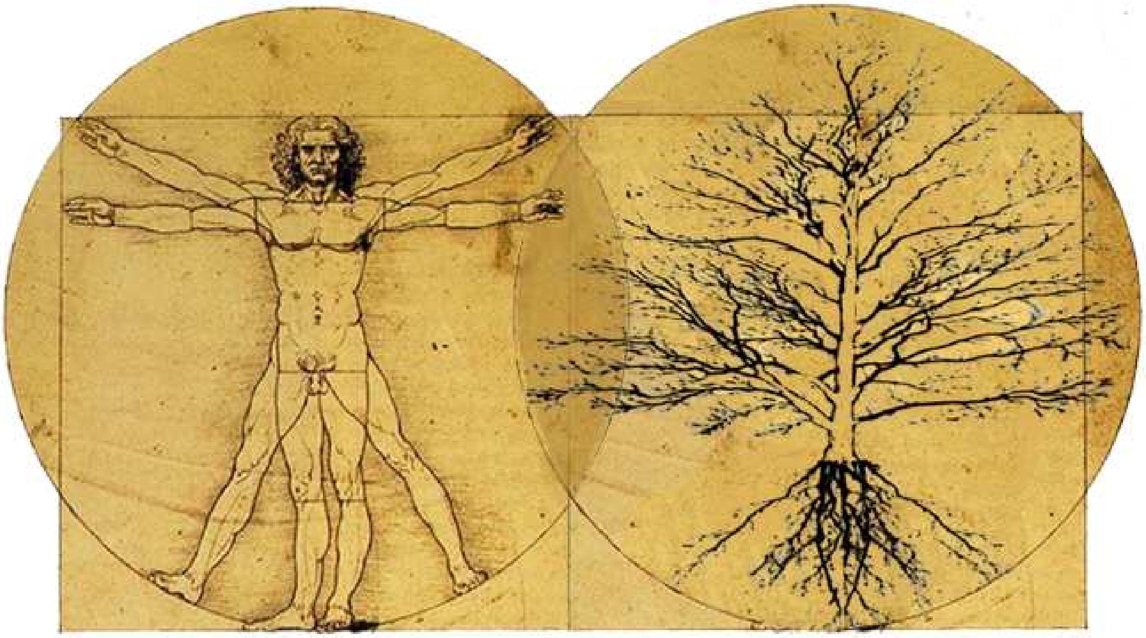


Figure 5.2. The Leonardo Living Couple. Courtesy of Steven Fiscus and Leonardo.

Descartes is similarly famous for helping to found modern science and philosophy and one of his most powerful and repeated quotes is “I think therefore I am.” This statement was made in the context of Descartes deciding that, in order to begin meaningful philosophical work and inner dialogue in which a key process is skepticism and doubting all apparent facts, he had to establish a foundation and starting point somewhere. He could doubt everything else, but “he could not doubt the doubter” or he would get lost in an infinite regress of self-doubt and would not be able to ever treat any facts as real, established, meaningful or true (Howard Pattee, email discussion list communication). But what if Descartes had focused more on continuous or *sustained thought* versus a discrete or short-term thought process and had said instead:

> "I think only as long as I have a steady input of oxygen, water and food to sustain my life and thinking. And after I am done thinking with aid of these materials, they are transformed into and expelled not so much as waste but as food for the plants and other living beings that in turn create and supply my material needs. I can only think, live and love in concert with their existence, and vice versa. I think, therefore, I am...we are...an ecosystem..."

Despite the historical anachronisms of many of the words and concepts, it is fun to imagine how the world might be different. To acknowledge this non-local basis for sustained thought and sustained life as distributed over at least two interdependent agents would be in a way to “doubt the doubter” and to acknowledge an infinite loop or cycle as required. Current works on self-reference (Bolander et al. 2006) and impredicative logic (Kercel 2003) show that such cycles need not be vicious or pathological. On the contrary, the holistic ecology espoused here even suggests such a cyclic basis for concepts of truth, life, mind, thought and action could hold the cure to our present environmental dysfunction and associated philosophical pathology of harmful ideas.

So if one adopted the ideas of ecosystemic life, ecological metaphysic, deep ecology or ecological self, what would one do? And would one likely fair well in the real world? Several example applications are next provided from the author’s local community activities.

One initiative is to develop pilot projects in permaculture – the art and science of “permanent agriculture” later generalized to “permanent culture” - developed by Bill Mollison (1996) and a colleague in the 1980’s in Australia. Permaculture mimics natural communities and ecosystems as basis for design of human agriculture and community. In Western Maryland this will involve planting fruit and nut trees, berry bushes and other perennial species so as to produce food while also building and improving soils. The basis for design and action is the community/ecosystem and accounting “bottom lines” include both production (food) and productive capacity (soils and biodiversity).

Another area of real application is the Cumberland, Maryland Sustainable Development and Restoration Economy Committee. This group works to promote synergy rather than conflict between environmental and economic community sectors, agencies and stakeholders. We have developed an initial set of indicators of sustainable community and produced and distributed a summary of recommendations for guiding local development toward conversion to renewable energy, ending car dependence, moving toward walkable and bikeable neighborhood designs and zoning ordinances, and turning environmental problems into entrepreneurial opportunities. Much of our work is available online (Cumberland Sustainable Development 2007).

Finally, several informal student and staff groups have emerged to discuss the environmental “footprint” and greenhouse gas emissions of the Appalachian Laboratory, Center for Environmental Science (UMCES) and Marine Estuarine and Environmental Science (MEES) degree program, all of the University of Maryland. These groups discuss and work on audits of campus emissions and proposals for improving environmental policy and performance. One action step is to get priorities added to the UMCES strategic plan setting goals to address environmental sustainability, convert operations to renewable energy and achieve net zero carbon emissions.

There are many other ideas and actions to discuss and explore. A list follows of lingering questions that could help build more confidence in the success potential of the ideas offered here.

When is knowledge limiting for change action for sustainability and when is something else limiting?

Do we need to define and clarify a complement to sustainability that is also a valid mode of action? That is, could sustaining and colonizing be different but interdependent modes of life action, both of which we need to value and pursue?

Are we seeing the need for “sustainable machines” or “lifelike machines” - machines re-invented based on coupled complementary construction and deconstruction capacities for open-ended existence and operation?

How can the works of Robert Rosen (1991) on complexity, non-computability, metabolism-repair models, closure to efficient cause, anticipatory systems and the modeling relation aid the holistic ecology ideas explored here?

Can an ecological metaphysic help with human happiness?

Can we relate Western science and Eastern philosophies in useful ways? Such as by contrasting that science seeks to *model everything correctly* with the goal being to know all or *never be surprised by observations not matching expectations*, while Tao and Zen and perhaps mystical Christianity seek to *model nothing* with the goal being to know peace and love and end suffering and also *never be surprised since one is not attached to any expectations*.

Can or should these diverse paths toward truth be expected to end up at the same place or some similar place?

Many people seem inclined to look at what we are doing now, or even extrapolate this further via growth, and ask "How can we sustain this?" We may also need to ask "What kinds of processes, and what sizes of systems and levels of activity, are sustainable?" Based on the answers, we may need to change to doing what is inherently sustainable and give up behaviors (and justifying behaviors) that cannot possibly be sustained.

How will we, how should we, allocate and utilize the remaining fossil fuels? What would be the best uses for these precious resources that are really a gift to all?

How can conscience, or "con-science", ethics, and religion inform science, systems knowledge, and action for sustainability?

Can we generalize the Golden Rule into an "Environmental Golden Rule"? Would this ethic or "action-thought" lead to environmental sustainability? Would it perhaps be: Do unto other – any other, including the environment – as you would have it do unto you. Could this serve as the necessary and sufficient, simple to say but hard to achieve, environmentally self-reflexive "theory of applied theory" we need to solve our environmental problems once and for all?

The potential for a concise, open-ended and democratic Environmental Golden Rule as generative concept to facilitate sustainable human-environment relations provides a note of hope and possibility on which to end.

Appendices

Appendix A. Reference values, conversion factors and other information for Chapter 3, The Self-Examination of Environmental Science as an Environmental Process.

Table A1. Literature values of N deposition, N fixation and total N inputs used in derivation of estimated forest N uptake and assimilation capacity.

Value (kg N ha^{-1} yr^{-1})	Description	Reference
1	pre-industrial N deposition	Goodale et al. 2002
1	non-symbiotic N-fixation in upland forests	Castro et al. 2001
1-2	background inputs to native ecosystems	Aber et al. 2004
1.5	N deposition to unpolluted forests	Galloway et al. 2003
2	NO_3 deposition in West Africa	Jordan and Weller 1996
2.4	NO_3 deposition in Amazon	Jordan and Weller 1996
2.71	N-fixation in forested lands modern day Potomac watershed	Boyer et al. 2002
4	N deposition in 1900 to Potomac watershed	Jaworski et al. 1997
6.76	wet NH_4 + NO_3 deposition Garrett County, MD 1996-97	Castro and Morgan 2000
6.8	deposition of NO_3 in Northeast U.S.	Jordan and Weller 1996
7	N deposition Hubbard Brook, NH	Aber et al. 2003
7.69	N deposition to Potomac watershed	Boyer et al. 2002
8	N deposition near Parsons, WV	Peterjohn et al. 1996
8-10	threshold of total N deposition before linear increases in NO3 export	Aber et al. 2003
10.8	N deposition to Chesapeake Bay watershed 1997	Castro and Driscoll 2002
12	highest N deposition in Northeast US, Adirondacks NY	Driscoll et al. 2003
14	deposition of NO3 in W. Germany	Jordan and Weller 1996
18	deposition of NO3 in Netherlands, Denmark, Great Britain	Jordan and Weller 1996
50-100	possible, extreme upper range of N deposition	Galloway et al. 2003

Table A2. Literature values of N uptake and forest production used in derivation of estimated forest N uptake and assimilation capacity and as related to N deposition.

Value (kg N ha^{-1} yr^{-1})	Description	Reference
7.1	low estimate, N uptake into live wood (from Forest Inventory and Analysis (FIA) data)	Goodale et al. 2002
9.2	high estimate, N uptake into live wood (from FIA data)	Goodale et al. 2002
11.96	N production in living wood	Currie et al. 2004
15	estimate of long-term immobilization, retention of N deposition in litter	Aber et al. 2004
19	total N production in wood, root and foliage minus local N recycling via mineralization	Currie et al. 2004, Aber et al. 2004.
27.72	N production in fine roots	Currie et al. 2004
63.8	N production in foliage	Currie et al. 2004
84	N mineralization, N supplied via local decomposition; low for temperate deciduous forests	Aber et al. 2004
1000	dissolved inorganic N retention on very N-poor soil; extreme case	Galloway et al. 2003

Table A3. Literature and online values of C uptake, sequestration and forest production used in derivation of estimated forest C assimilation capacity.

Value (kg C ha^{-1} yr^{-1})	Description	Reference
600	Average for all U.S. forests	Dixon et al. 1994
2000	low estimate, Harvard Forest	Schmid et al. 2000
2360	Indiana forest	Schmid et al. 2000
3600	Potential or maximum rate for Maryland deciduous forests	Niu and Duiker 2006
4220	Walker Branch, TN 1997	Schmid et al. 2000
4500	Estimate using TNC carbon sequestration tool and doubling estimate for soils role	TNC 2006 (online tool)
4650-4820	NPP* carbon in Wisconsin northern hardwoods 1999, 2000	Ahl et al. 2004
5000	high estimate, Harvard Forest	Schmid et al.2000
5250	Walker Branch, TN 1993-1994	Schmid et al. 2000
5850	Oak-hickory forest, Walker Branch, TN	Malhi et al. 1999

* Note: NPP = net primary productivity.

Table A4. Literature and online values of C, energy, N and water input and output for humans.

Value and units	Description	Reference
Energy (kcal person^{-1} day^{-1})		
2000-2500	FDA food labels	Most U.S. food labels
2002	U.S. average 1994-1996	USDA 1998
2823	NASA astronauts	Hanford 2004
Carbon (kg C person^{-1} day^{-1})		
0.228	C output in respiration	Taub 1974
0.255	C intake in food, average of male and female estimates	Snyder et al. 1974
0.270	C output in respiration	Snyder et al. 1974
0.272	C output in respiration, astronauts	Hanford 2004
0.282-0.326	C output in respiration in closed life support system for astronauts	Czupalla et al. 2005
0.0128	C output in urine, feces and other losses	Snyder et al. 1974
Nitrogen (kg N person^{-1} day^{-1})		
0.00753	N output in sewage	Gajdos 1998
0.0079	N output in sewage	Schouw et al. 2002
0.011	Estimated from 80g protein	Jacks et al. 1999
0.013	N intake in food	Boyer et al. 2002
0.0145	N intake in food, average of male, female	Snyder et al. 1974
0.0154	N output in urine and feces, average of male, female	Snyder et al. 1974
0.0156	N output in sewage	Heinonen-Tanski 2005
Water (kg H_2O person^{-1} day^{-1})		
2.4	Drinking water input	Taub 1974
2.73	Total water output	Taub 1974
3.56	Drinking water input for closed life support system for astronauts	Hendrickx et al. 2006
3.857	Drinking water input for closed life support system for astronauts	Czupalla et al. 2005
3.909	Water input for NASA astronauts	Hanford 2004
4.254	Total water output	Hanford 2004

Table A5. Solar and wind energy estimates for area near Frostburg, Maryland.

Value and units	Description	Reference
Solar energy (kWh m^{-2} yr^{-1})		
167	Estimate of solar energy captured in primary production in Maryland assuming light use efficiency of 0.5 g C per megajoule of PAR and 3000 kg C per ha per year	Ahl et al. 2004
258	Estimate of solar energy captured in primary production in Wisconsin assuming light use efficiency of 0.51 g C per megajoule of PAR and 4735 kg C per ha per year	Ahl et al. 2004
584	Average annual photosynthetically active radiation (PAR), measured, Pennsylvania	SURFRAD 2006 (online)
1,351	Average annual total solar radiation, measured, Pennsylvania	SURFRAD 2006 (online)
1,643	Estimated average annual total solar radiation assuming a flat panel collector tilted south	NREL 2006 (online)
Wind energy (kWh m^{-2} yr^{-1}, vertical area)		
1,752	Using 200 W/m^2 day as the maximum of a class 3 wind site	Elliot et al. 1986. NREL Wind Atlas (online)

Table A6. Conversion factors.

Conversion	Factor or value	Units	Reference or method
Electricity to CO_2 emission (by year)			
1997	2066	lbs / MWh	Allegheny Power1
1998	2020	lbs / MWh	Linear interpolation
1999	2000	lbs / MWh	Linear interpolation
2000	1991	lbs / MWh	eGRID 2006
2001	1730	lbs / MWh	Linear interpolation
2002	1500	lbs / MWh	Linear interpolation
2003	1268	lbs / MWh	Allegheny Power1
2004	1195	lbs / MWh	Allegheny Power1
2005	1195	lbs / MWh	Used 2004 value
Comparison value	1640	lbs / MWh	Easter 2002
Natural gas to CO_2 emission	5.91	kg CO_2 / therm	WRI 2006 spreadsheet
Comparison value	5.08	kg CO_2 / therm	CDIAC 2006
Air travel to CO_2 emission (by trip length)			
less than 452 km	0.18	kg CO_2 / passenger km	WRI 2006
452 – 1600 km	0.13	kg CO_2 / passenger km	WRI 2006
more than 1600 km	0.11	kg CO_2 / passenger km	WRI 2006
Automobile travel (gasoline) to CO_2	8.87	kg CO_2 / gallon gasoline	WRI 2006
Comparison value	16.34	kg CO_2 / gallon gasoline	Easter 2002

Notes:
1. Allegheny Power - “Energy Source (Fuel Mix)” and “Air Emissions” disclosure sheets

Table A6, continued. Conversion factors.

Conversion	Factor or value	Units	Reference or method
Electricity to NOx emission (by year)			
1997	5.6	lbs / MWh	Allegheny Power
1998	5.29	lbs / MWh	Linear interpolation
1999	4.96	lbs / MWh	Linear interpolation
2000	4.63	lbs / MWh	eGRID 2006
2001	4.05	lbs / MWh	Linear interpolation
2002	3.52	lbs / MWh	Linear interpolation
2003	2.998	lbs / MWh	Allegheny Power
2004	2.86	lbs / MWh	Allegheny Power
2005	2.86	lbs / MWh	Used 2004 value
Natural gas to NOx emission (AL boiler)	100	lbs / 1000 cu. ft.	WebFIRE 2006
Automobile travel to NOx emission	0.256	g NOx / mile	Davis and Diegel 2002
Gasoline use efficiency	24.1	miles / gallon	Davis and Diegel 2002
Air travel to NOx emission	0.86	g NOx / passenger mile	National Academy Press 2002
Comparison value	0.89	g NOx / passenger mile	NASA 2003
Electricity kWh to megajoules	3.6	megajoules / kWh	Davis and Diegel 2002
Natural gas to energy	1027	Btu / cu. ft.	Davis and Diegel 2002
Comparison value	1031	Btu / cu. ft.	EIA 2006
Air travel to energy use	4000	Btu / passenger mile	Intermediate between two values below
Average value, 1999	4061	Btu / passenger mile	Davis and Diegel 2002
Average value, 2000	3952	Btu / passenger mile	Davis and Diegel 2002
Gasoline to energy	130.88	megajoules / gal gas	EIA 206
Comparison value	130.88	megajoules / gal gas	Davis and Diegel 2002

Appendix B. Network dataset, reference values and other information for Chapter 4, Comparative Network Analysis Toward Characterization of the Necessary and Sufficient Organizational Criteria for Environmental Sustainability.

Table B1. Humans-beef nitrogen network matrix of stocks and fluxes. Fluxes in kg N/yr, stocks in kg N. System scaled to Allegany County, Maryland in 2005. Exports and respirations continued on next page.

Beef supply chain													
No of Compartments		12											
No of Living Compartments		9											
		1	2	3	4	5	6	7	8	9	10	11	12
		grasshay	corn	cowcalf	feedlot	slaughter	transport	retail	home-rc	humans	fertilizer	soil	WWTP
1	grasshay			828903	78859							680822	
2	corn				328581							140180	
3	cowcalf				42500							666483	
4	feedlot					93993						322315	
5	slaughter						86390						
6	transport							85534					
7	retail								84337				
8	home-rc									75871			4215
9	humans												74621
10	fertilizer											700000	
11	Soil	1710625	612675										
12	WWTP												
	Imports	0	3286	31466	30668	0	0	0	0	0	4673706	1386218	0
	Biomass	453881	32858	136287	69700	43	473	234	463	17250	42000	94250000	72

Table B1, continued. Humans-beef N network, vectors of exports and respirations. Fluxes in kg N/yr.

Cpt	Compartment	Exports	Respirations
1	grasshay	75000	5000
2	corn	144180	4000
3	cowcalf	138464	3585
4	feedlot	61393	2091
5	slaughter	7091	513
6	transport	0	855
7	retail	599	599
8	homerc	0	4215
9	humans	625	625
10	fertilizer	3706	3970000
11	soil	1567867	5000
12	WWTP	57244	21527

Table B2. Beef nitrogen (N) network dataset – selected flux values and references. All attributes refer to N in beef unless stated otherwise. All units are kg N/yr unless otherwise noted.

Attribute	Value	Reference or method
Human ingestion of N in beef	75,871	Calculated from average per capita beef consumption, protein and N content
Human purchase of N in beef	84,337	Assume 10% loss (total mass) at home due to prep, cook, unused, spoilage
Waste beef N to landfill, sewage	4,215	Each as 5% losses of home preparation
Export N in human sewage	74,621	Ingested N excreted
Transport of N from slaughter-packing to retail	85,534	Calculated using 32% loss from Gregory et al. 1994
N lost due to condemned animals	513	Calculated from NASS 2006
N in live cattle transported from feedlot to slaughter	93,993	Calculated using 38% loss from NASS 2006
N lost due to death at feedlot	2091	Calculated from NASS 2005
N in manure from feedlot to soils	260,921	Calculated using Aillerry et al. 2005
N exported from feedlot manure to atmosphere	99,764	Calculated using Aillerry et al. 2005
N exported from feedlot manure to runoff, leaching	23,022	Calculated using Aillerry et al. 2005

Table B3. Selected reference values used in construction of the beef network.

Attribute	Value	Units	Reference or method
Retail, Home, Human Ingestion			
Percent protein in beef	27.2	percent	Average from USDA 2006a nutrition data
Percent water in beef	59	percent	USDA 2006a
Percent N in protein	16	percent	USDA 2006a
Percent N in lipid free beef muscle	12	percent	Bahar et al. 2005
Percent N in protein	17	percent	Sterner and Elser 2002
Percent loss of total mass at home, restaurant	10	percent	Smil 2002
Per capita beef ingestion	23.2	kg person^{-1} yr^{-1}	Calculated using 10% loss at home from 2005 retail supply
Per capita beef ingestion	12.8	kg person^{-1} yr^{-1}	Sum of ground beef and steak ingestion 1994-1996 USDA 1998, 2006a
Retail			
Per capita beef supply at retail	25.8	kg person^{-1} yr^{-1}	Calculated using estimate of 32% loss from Gregory et al. 1994
Per capita retail supply for 2005	66	lbs person^{-1} yr^{-1}	USDA 2000b
Slaughter-Packing			
Per capita beef production	83.7	lbs person^{-1} yr^{-1}	Calculated using 2005 U.S. production and U.S. population
Percent animals condemned at slaughter	0.55	percent	NASS 2006
Percent loss from live to dressed carcass	39	percent	Calculated using NASS 2006
Percent loss from live to dressed carcass	40	percent	Gregory et al. 1994
Percent loss from packing to retail	32	percent	Calculated from Gregory et al. 1994
Head of cattle to supply beef	8200	head	Calculated using total live production per capita and 75,000 people
Average live steer	570	kg	NASS 2006

weight at slaughter			
Feedlot			
N in live cattle as percent of weight gain	1.6	percent	Hao et al. 2005
Percent N dry mass for large mammal	7.2	percent	Sterner and Elser 2002
Percent N wet mass for large mammal	2.2	percent	Calculated using Sterner and Elser 2002
Percent N live cattle, **value used**	2.0	percent	Intermediate between above and near Sterner and Elser
N content of cattle manure, dry mass	1.4	percent	Ferguson et al. 2005
N content of cattle manure, dry mass	1.6	percent	Larney et al. 2006
N content of cattle manure, dry mass	2.5	percent	Hao et al. 2005
N content of cattle manure, dry mass	2.8	percent	Vasconcelos et al. 2006
Percent manure N lost to runoff and leaching	6	percent	Aillerry et al. 2005
Percent manure N lost to air	26	percent	Intermediate between Eghball et al. 1997 and Aillerry et al. 2005
Cow-calf			
Average weight at birth	37.2	kg	Tess and Kolstad 2000b
Average weight at weaning	250	kg	Pollan 2006
Number of months nursing	7	months	Tess and Kolstad 2000b
N input in feed for cows	81	kg N yr^{-1} per head	Calculated from Tess and Kolstad 2000b
N input in feed for calf	7.1	kg N yr^{-1} per head	Calculated from Tess and Kolstad 2000b
N output in manure per cow	68.4	kg N yr^{-1} per head	Calculated from Tess and Kolstad 2000b
N output in manure per calf	13.7	kg N yr^{-1}	Calculated from Tess and Kolstad 2000b
Corn, hay and grass			
N in grass silage, dry	2.2	percent	Bahar et al. 2005
N in corn silage, dry value use for corn	1.3	percent	Bahar et al. 2005
N in corn kernels	0.97	percent	Peterjohn and Correll 1984

N in native range grass, dry	1.8	percent	Calculated from Tess and Kolstad 2000b
Weight of a bushel of corn	25	kg	Baker and Allen 2006
Corn yield 1981 in Delaware	222	bushels ha^{-1}	Peterjohn and Correll 1984
Corn yield 2005 in U.S.	365	bushels ha^{-1}	Baker and Allen 2006
Corn N uptake	250	kg N ha^{-1} yr^{-1}	Peterjohn and Correll 1984
Corn N demand	252	kg N ha^{-1} yr^{-1}	Ferguson et al. 2005
Miscellaneous			
U.S. population 2005	296,410,404	people	U.S. Census Bureau 2006
Total 2005 beef production U.S., live weight	40.7	billion lbs	USDA 2006b
Total 2005 beef production U.S., dressed carcass weight	24.8	billion lbs	NASS 2006
Per capita beef production	83.7	lbs person^{-1} yr^{-1}	Calculated from total U.S. population and production

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