Turning small snapshots into a bigger picture for sustainability

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ABSTRACT

The broader scientific community is slowly coming to grips with the concept of sustainability. An inherent difficultly with this concept has been that, unlike traditional scientific investigations that seek to explain how things currently function or how previous events led to current phenomena, sustainability research is forward-looking with the goal to understand how both current, and indeterminate future, societal needs can be met. This goal is further constrained by an imperative for maintaining ecological and environmental integrity. This conference addresses several important themes pertinent to the challenge of sustainable ecosystems: data collection and monitoring of natural systems and their components, analysis of those data in the context of biophysical ecosystem models, and application of model outputs to environmental and economic issues for management and policy making. Ecological scale and systems science are two important, but often underappreciated, concepts that are critical for advancing our understanding of sustainability. New sustainability sciences, appearing at the interface of traditional disciplines, are better poised to integrate these concepts. The most important objective of our data collection and modeling efforts will be to anticipate sustainability problems and recommendation alternative courses of action, while aiding social learning by the non-scientific community.

Keywords: Ecological scale, systems science, sustainability sciences, R&D, precision agriculture, ecosystem models.

1. INTRODUCTION

Before the agricultural revolution began in the 9th century, all agriculture was local.[1] The producer was the consumer and was responsible for managing the small ecosystem that comprised the tribe, or family, garden (and the manor wherein they lived and worked). The segregation of producer from consumer that followed the introduction of the *new* agriculture (i.e., large quantities of food produced primarily by a fixed segment of the workforce) enabled non-agricultural laborers to congregate in cities and changed socio-economic traditions forever. The city-dwelling sector of the population developed a merchant/business class that was now disconnected from the land, setting in motion a course of events that has resulted in a current population (at least in the developed countries) that is largely ignorant of agriculture and food production—despite food's obvious importance to human well-being. If intellectual engagement and a sense of land ethic are important factors to popularize sustainable land management practices,[2-5] then these long-standing historical and cultural contexts have ill-prepared most people to tangibly accept and understand the notion of sustainability.

The more recent, industrial revolution of the 19th century rapidly increased agricultural productive capacity through increased energy, power, industrial and chemical products, and improved plant varieties. Particularly during the 20th century, agricultural productivity increased markedly—due in large part to technological changes emanating from scientific advances—while overall agricultural inputs declined slightly (Figure 1). While this reduction in farm inputs might appear to be favorable for sustainability, in fact, it has been the drastic reduction in labor and land expenses that offset large increases in fertilizer and pesticide use (Figure 2). Specialization in commodity production within an industrial framework has resulted in tremendous production levels but, due to stagnant commodity prices and high chemical use, has also reduced environmental quality and rural prosperity.[6] Publicly funded agricultural research has, at least indirectly, encouraged this commodity focus.[7] Innumerable scientific studies have already documented the deterioration of soil and water quality resulting from past and current agricultural practices. Considerable additional work is now underway to identify alternative practices and technologies that demonstrate sustainable economic, environmental, and societal benefits.

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Remote Sensing and Modeling of Ecosystems for Sustainability,
edited by Wei Gao, David R. Shaw, Proceedings of SPIE Vol. 5544
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.564915

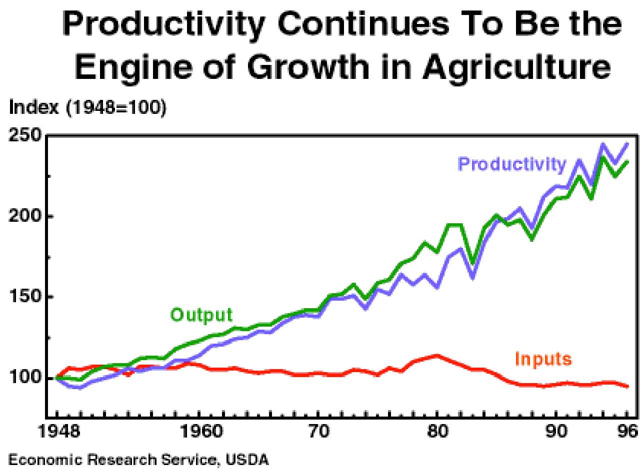

Figure 1. Agricultural productivity and outputs increased dramatically, while inputs decreased slightly (in constant dollars, 1948=100) during the latter half of the last century.* Outputs reflect the total value of farm production (sold and inventoried); inputs account for the total expenditures used in production (including land, labor, materials, etc.). Productivity is the ratio of output and input indices.

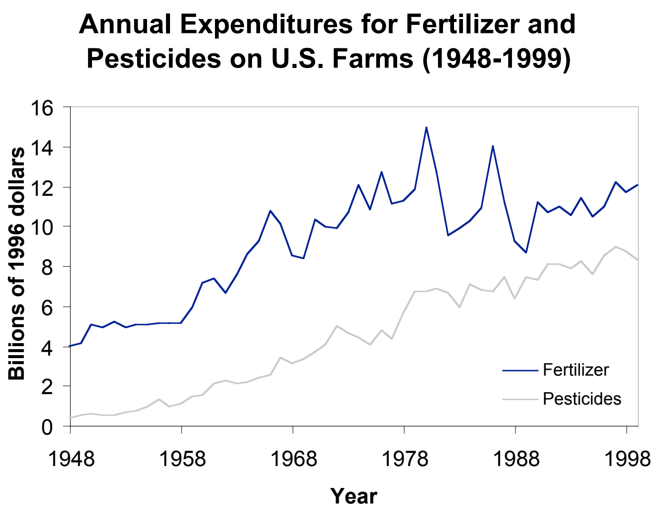

Figure 2. Both fertilizer and pesticide expenditures increased on U.S. farms during the latter half of the 20th century,† offsetting large reductions in labor and land expenditures.

Despite the agricultural disconnectedness of a large segment of most developed countries' inhabitants, we have gradually increased world-wide land management to meet the food and fiber needs of a growing global population. According to the FAO‡ as of 1995, cropland, forage land, and forest land made up over two-thirds of the Earth's land area. Much of this land is under production and, hence, much of our landmass falls within the category of *managed ecosystems*. At the same time, another seven percent of the world's land area resided in nationally protected areas (and continues to grow), which also receive varying levels of management. So, while we are well-positioned managerially—owing to extensive land areas currently under active management—we lack the scientific understanding, management tools, favorable national policies, and ideological momentum to effectively address sustainability issues.

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* USDA, Economic Research Service, http://www.ers.usda.gov/Briefing/AgResearch/Questions/APRDQA2.HTM, 2002.
† USDA, Economic Research Service, http://www.ers.usda.gov/Data/AgProductivity/#data, 2002.
‡ USDA, Economic Research Service, http://www.ers.usda.gov/Briefing/GlobalResources/Questions/table4_1.htm, 2002.

It is especially important, then, that an international scientific conference dealing with ecological and environmental monitoring focuses on sustainability. Satellite and air-borne sensing platforms offer the obvious advantages of extensive geographic coverage, repeated measurements over time, simultaneous measurement of biological, physical, and infrastructure features, and ready access (weather permitting). Those data, however, need to be organized, analyzed, and interpreted within the proper ecosystem context, using models of ecosystem processes. This provides the data with biophysical meaning and empowers them with scientific, managerial, and policy importance. The next section of this paper examines some of the research and policy directions that could be drivers for studies involving remote sensing, ecosystem modeling, and sustainability. Following that agenda setting exercise, the paper argues that to truly address sustainability questions, current and future scientific investigations must surmount two methodological difficulties—ecological scale and systems thinking. Finally, the last section offers some insights into what these things might imply for science, in general, and for scientific studies of ecosystems, in particular.

2. RESEARCH AND POLICY DIRECTIONS

2.1. R&D expenditures

Before discussing any research issues, we must first examine federal spending for research and development (R&D), as it provides a broad perspective of national investments. Federal nondefense R&D has hovered at about two percent of the total federal budget for the past 20 years[*] Actual nondefense R&D expenditures (constant dollars) have increased steadily since the early 1980's but, when adjusted for long-term increases for the National Institutes of Health, have only recently returned to their high point of the 1978-1981 era (Figure 3). Based on 2005 budget requests, only the Dept. of Homeland Security will realize significant increases (>10%) in the coming year. Most agencies are project to suffer constant-dollar budget decreases over the next five years (Figure 4). Projected tighter budgets for nondefense R&D will constrain what each agency can do individually. Only the most readily defended programs in an agency will be competitive in an increasingly austere spending environment. With greater frequency, agencies will need to collaborate and pool resources to keep less-viable, but yet important, program areas supported.

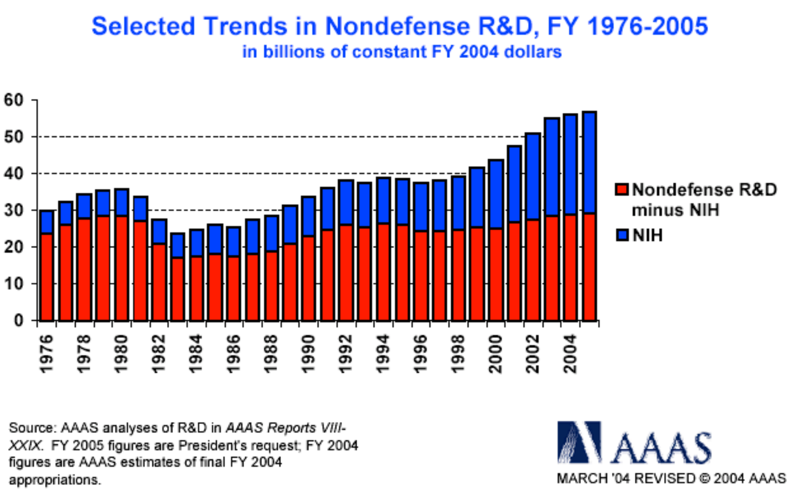

Figure 3. Overall nondefense R&D has increased over time, but the increase has occurred primarily in the budget for NIH. Reprinted by permission from the American Association for the Advancement of Science.

Even those non-NIH numbers in Figure 3 mask a great deal of variability in budget trends between agencies. Because federal-wide R&D expenditures are tracked primarily at the level of departments and independent agencies (e.g., Dept. of Agriculture, National Science Foundation), it is difficult to discern how annual appropriations vary historically for individual agencies within a large, diverse department, such as the Cooperative State Research, Education & Extension Service (CSREES) in the Dept. of Agriculture. After closer examination, however, CSREES budgets can be seen to

[*] American Association for the Advancement of Science, http://www.aaas.org/spp/rd/guihist.htm, 2004.

have fluctuated, in constant dollars, over the past decade (Figure 5), only recently returning to mid-1990 levels. More importantly, the relative distribution of appropriations has changed over time. Recent disproportionate increases in competitive funding programs and Congressionally directed line-items have risen to approximately one-third and one-sixth of the agency budget, respectively. These changes have begun to influence the types of agricultural problems and issues addressed by the agency. In the case of competitive programs, the agency has greater discretion in directing research dollars to issues it perceives as critical, and in the case of budgetary line-items, constituents draw attention to problems that warrant Congressional action through our agency.

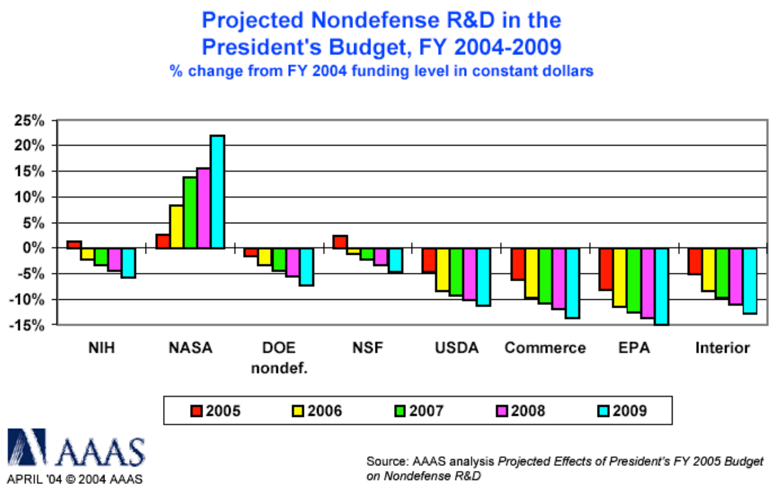

Figure 4. Projections of nondefense R&D are downward for most federal agencies. Reprinted by permission from the American Association for the Advancement of Science.

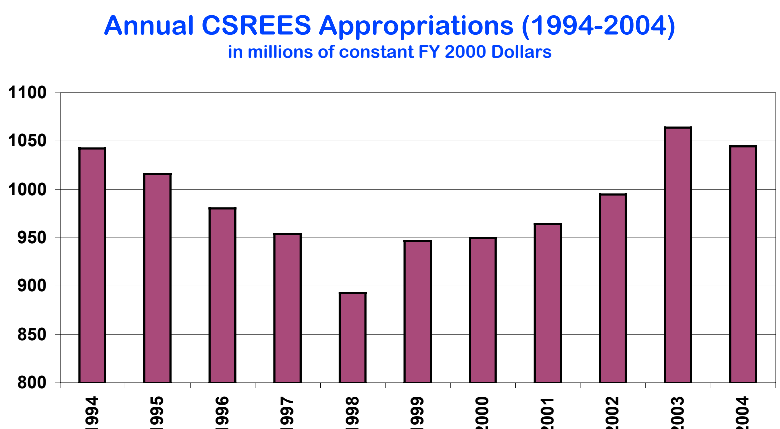

Figure 5. CSREES annual appropriations have experienced dramatic swings in the past decade.

2.2. Current R&D directions

Given that some fixed amount of funds is available each year, it is probably of greater importance, then, what areas of investigation those dollars support. While CSREES doesn't have a good historical perspective for relative outlays across various agricultural issues—which can, and do, change over time—we can look at those policies, directives, and scientific agendas that are currently, or likely to be, high priorities. Sources of influence for agency R&D expenditures are many. Some influences direct programmatic change quite directly, while others are more indirect and gradual. For the intents and purposes of this conference, it makes sense to limited our focus to those issues closely related to ecosystems, sustainability, and the environment.

2.2.1. Land-grant institution priorities

Security issues have taken center stage in both executive and legislative branches of the federal government in the past several years. These now also include agricultural and food security. Most of the increased interest in this area is related to possible intentional acts of contamination or damage. However, if ecosystems are compromised through unintentional acts (e.g., anthropogenic disturbances), agricultural production and food supplies can also be disrupted. In 2001, the National Association of State Universities and Land-Grant Colleges (NASULGC) formulated a roadmap[8] for agricultural research over the next two decades. That report identifies seven challenges. Three of them deal with environmental systems; these are listed below with the associated scientific foci noted in the report.

Lessen the risks of local and global climatic change on food, fiber, and fuel production.

- Diminishing the rate of long-term global climatic change by increasing the storage of carbon and nitrogen in soil, plants, and plant products;
- Minimizing the effects of long-term global climatic changes on production of crops and livestock;
- Integrating long-term weather forecasting, market infrastructures, and cropping, and livestock management systems to rapidly optimize domestic food, fiber, and fuel production in response to global climatic changes; and,
- Creating broad-based, comprehensive models to assess the socioeconomic impacts, risks, and opportunities associated with global climate change and extreme climate events on agriculture.

Provide the information and knowledge needed to further improve environmental stewardship.

- Developing better methods to protect the environment both on and beyond the farm from any negative impacts of agriculture through optimum use of cropping systems including agroforestry, phytoremediation, and site-specific management;
- Decreasing our dependence on chemicals with harmful effects to people and the environment by optimizing their use in effective crop, weed, pest, and pathogen management strategies;
- Finding alternative uses for the wastes generated by agriculture; and,
- Developing better economic models and incentives to assure that environmental stewardship is encouraged.

Improve the economic return to agricultural producers. [*]

- Designing improved decision support systems for risk-based management farming (giving full consideration to small-, medium- and large-scale enterprises);
- Developing sustainable production systems that are profitable and protective of the environment, including ways to optimize the integration of crop and livestock production systems;

Quickly scanning these lists, one notices that economic, social, and environmental questions are all mentioned. More generally, science is currently lacking to: inform us about what we don't currently know, help us apply the knowledge we do have, and project the impacts of current and future practices. These three scientific themes are entirely consistent with this conference's intents and the papers offered.

2.2.2. Healthy forests

Many years of wildfire exclusion from forests in the U.S. have dramatically altered historical fire regimes (fire frequency and intensity) and simultaneously fire-dependent ecosystems.[9] Extreme fuel loadings, persistent drought conditions in the western U.S., and the socioeconomic impacts of yearly uncontrolled wildfires have generated considerable public and scientific dissatisfaction. Consequently, a number of provisions in the recently enacted Healthy Forests Restoration Act of 2003 (P.L. 108-148) are intended to address those national concerns. In general, the Act aims to: reduce wildfire risk, better utilize forest biomass, enhance watershed protection, control insect and disease outbreaks, and protect, restore, and enhance forest ecosystem components (Sec. 2). The Act authorizes federal funds to meet the specified obligations, but future budget appropriations are still needed to make funds available in agency budgets.

Several sections of this legislation fit well within the context of remote sensing and ecosystem modelling capabilities. While fuels reduction projects are an important aspect of this Act, identifying and prioritizing land units for fuel treatment could readily benefit from large-scale assessments using imagery and geographic information systems. This

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[*] Only the two *environmental* foci are listed here, out of the four foci mentioned in the report.

applies equally well to monitoring insect and disease outbreaks and their impacts (mortality, defoliation). Furthermore, areas at risk to attack could be delineated based on ecological models of interactions among forests, insects, diseases, and climate. These assessments could also be tied into economic models to aid strategic planning and policy statements.

The Act also makes changes to two other, existing pieces of legislation. Title II, dealing with biomass, adds a clause to the Biomass Research and Development Act of 2000 (P.L. 106-224) that expands the list of researchable topics to include the integration of silviculture, harvesting, products, processing, and economics. Again, these are subjects that could make use of remotely sensed data, spatial data tools, and, perhaps, silvicultural/ecosystem models. Title III adds a section to the Cooperative Forestry Assistance Act of 1978 (P.L. 95-313) to address watershed projects. Owing to the large acreages encompassed by watersheds and the many needs for water quality, forest management, and riparian areas, remotely sensed data and models could be very beneficial. Furthermore, as one looks across the many agencies that deal with water quality or quantity issues—and examines the recent budget trends—it becomes readily apparent that "water" has been increasing dramatically in political and scientific importance.

Because insect and disease induced mortality in western forests has been responsibility for much of the current fuels loads, Title IV of the Act deals entirely with these, and other, damaging agents. A primary focus of this legislation is "accelerated information gathering," including models to predict occurrence, distribution, and impacts. Finally, a related title of this Act establishes a "forest stand inventory and monitoring program," intended to aid better understanding of early detection of environmental threats, forest degradation, forest regeneration, carbon uptake rates, and forest-degrading management practices. Presumably, much of this data collection will be on the ground, but it could be supplemented with remote data collection and modelling activities.

2.2.3. National Research Council

Chartered by Congress, each year the National Academies respond to requests from Congress, federal departments and agencies, and other institutions to produce unbiased scientific evaluations on a variety of topics. The National Research Council (NRC), though a variety of divisions and committees, is the arm of the National Academies that conducts those evaluations. Because of the large number of reports completed each year, published reports appear on a regular basis that are pertinent to agriculture, food, and natural resources. I will highlight two of those, one produced almost eight years ago and addressing a very specific topic (precision agriculture), and the second, published recently, covering agricultural research generally.

In 1997, the NRC established some guidelines for the role of public institutions with regard to research, development, and dissemination of precision agriculture (PA) technologies.[10] The committee generating that report defined PA as the application of information technologies to bring data from multiple sources to bear on crop-management decisions. Much as NASULGC listed challenges, above, this NRC report's statements can also be viewed as challenges for the agricultural sciences.

- *PA requires new approaches to research that are designed explicitly to improve understanding of the complex interactions between multiple factors affecting crop growth and farm decision making.* The report continues on to note that this will require a systems approach to experimental research, which also implies highly interdisciplinary efforts.

- *The potential of PA is limited by the lack of appropriate measurement and analysis techniques for agronomically important factors*. That is, existing technologies were not designed for the sampling frequencies and resolutions required by PA.

- *Data collected at the field scale can be assembled into regional data bases. Mechanisms are needed to find value in these data by: establishing data collection and interchange standards; creating institutions for collecting, managing, and networking data; and developing policies to facilitate data sharing and access while ethically protecting ownership interests and confidentiality.*

- *Unbiased, systematic, and rigorous evaluations of the environmental and economic costs and benefits of PA methods are needed*. PA covers a wide variety of techniques across variously parameterized scenarios, including different products/resources, environments, and management needs. The PA "discipline" needs to

> develop a better conceptual understanding of how all these different parameters fit together. Right now, this is only being done on a case-by-case basis. Until we can make these connections in a very general way, PA will always be viewed as a grab-bag of technologies that sometimes work and sometimes do not.

More recently (2003), the NRC was charged with providing direction for the four agencies that conduct most of the research in the U.S. Dept. of Agriculture.[11] Three NRC subcommittees were involved in these deliberations, one of them focused on environmental quality and natural resources. Their observations and recommendations should be of interest to anyone engaged in related areas of research and development. Five broad issue areas were identified: (1) globalization of the food economy, (2) emerging pathogens and other hazards in the food-supply chain, (3) enhancing human health through nutrition, (4) improving environmental stewardship, and (5) improving quality of life in rural communities. Within issues #1 and #4, the report made a number of recommendations related to sustainability, ecosystems, remote sensing, and associated topics.

- Workable decision support tools based on precision agriculture are need that will enable producers to adjust the timing and amount of production inputs while minimizing waste and environmental impacts.

- Understanding the effects of new technologies, e.g., genetically modified organisms, will require improved risk assessment and communication methods, and enhanced ecosystem models and other analytic frameworks.

- We need increased understanding of off-farm transport of agricultural contaminants and better strategies for keeping agricultural inputs and soils within the farming system.

- Large gaps exist in our ability to predict and mitigate species invasions.

- We need a greater understanding of the production of ecosystem and environmental services from agricultural lands, e.g., biodiversity, carbon sequestration, and water quality, and ways to measure and monitor those benefits.

- Environmental research needs to address appropriate geographic and time scales so that results will have relevance to long-term changes. In addition, there needs to be a better integration of leading-edge environmental science concepts with emerging technologies.

Conspicuously missing from this list is any explicit mention of social systems and the need to integrate our environmental agenda with human values and expectations. The final bullet provides a topical segue into two important issues that will help determine how effectively ecosystem studies can increase our knowledge of sustainability and our ability to turn that knowledge into realistic action items.

3. ECOSYSTEMS AND SUSTAINABILITY

Sustainability is inextricably link to our understanding of ecosystems. Without a clear picture of ecosystem structure and functioning, it is difficult to determine whether current management practices are consistent with long-term ecosystem health and stability. In turn, our understanding of ecosystems is dependent on our ability to measure ecosystem components and to integrate those individual components within a conceptual, mathematical, or algorithmic representation (or model) that mimics overall system behavior. As strongly as this suggests a *systems science* approach to research, in practice it has not materialized as naturally as might be expected. Much ecosystem research still focuses on individual components, intent on describing all aspects of a particular ecosystem component while only making mention of its relative position within a larger system. Those investigations that do apply systems science methods often focus solely on biophysical aspects of the system, ignoring socioeconomic components.[12] The latter are often especially critical when crafting a successful *systems solution* to a sustainability problem. Those problems and their solutions are often most evident at larger scales, e.g., watershed scales or climatological scales. However, it is only at much smaller geographic scales and shorter time frames where research funding limits allow us to conduct scientific investigations.[12,16] While there is abundant awareness of scale in ecology, its treatment is, in many cases, either inconsistent or infrequent.

3.1. Systems science

We are all familiar with the interacting-circles perspective of system science as illustrated in Figure 6. In fact, the importance of this approach to agriculture was recognized almost a century ago.[13] Each circle represents a major conceptual system, often drawing upon the knowledge contained within a number of traditional scientific disciplines. These traditional scientific "schools" of thought continue to act separately, in most cases, as they search for answers to sustainability questions. Viewed in the light of most current scientific investigations, the areas of intersection are, in practice, much smaller than depicted here. Within each of these three components, there are multiple systems, and within each of those systems there are many other subsystems nested hierarchically—lower "levels" containing fewer processes or interactions than more complete "levels" above. What is not depicted in this diagram is *scale*. Regardless of the system or subsystem that one is examining, it can be studied at many different scales as noted below.

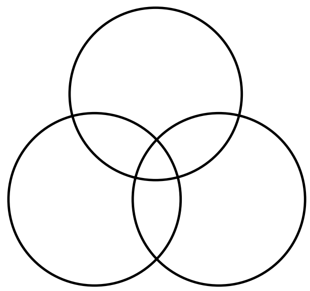

Figure 6. Any conceptualization of systems science includes the idea of interrelated components. Others may label the circles differently (e.g., environmental, social, economic), but the essential notions are the same.

In the past, our view of dynamic systems has been one of measured, regular, and timely system behavior in response to perturbations. While this was consistent with small-scale, controlled experiments and our sense of Newtonian regularity, it was not, in fact, realistic. Complexity science and catastrophe theory suggest that systems evolve and behave quite different. There are critical thresholds, cusps on response surfaces, chaotic behaviors, state changes, and lag-time responses that are more reflective of real-world system dynamism than our prior expectations for monotonicity. These revised expectations for systems behavior will require changes to our scientific thinking, including the types of experiments conducted, analyses performed, conclusions drawn, and application to sustainability problems.

The evolution of an effective systems science approach to sustainability will struggle with a number of hurdles. First, our whole body of scientific knowledge is organized around disciplines as distinct and somewhat separate endeavors. Commensurate with that body of knowledge, our institutions of higher learning are organized similarly—disciplinary departments, schools, and colleges reflect that historical taxonomy. Furthermore, new scholars are encouraged to, and rewarded for, developing specialization in one narrowly defined subdiscipline. In some sense, we are training myopic savants rather than well-schooled scholars and scientists. Second, much of our knowledge of agroecosystems has been gleaned from relatively short-term experiments. There are many obvious, and some not so obvious, advantages to conducting long-term agroecosystem experiments.[14] Even the longer term experiments that have been conducted have only looked at biophysical components in most cases. For intensively managed agricultural lands, longer term research is needed to better understand both biophysical and socioeconomic systems and their interactions. Third, sustainability research is currently conducted to completion, with results subsequently handed off to policy makers or to managers. There is often little or no interaction with stakeholders from the outset to properly contextualize and circumscribe the issues. To make system science research maximally beneficial, stakeholders need to be involved early on so that the proper issues are studied in the correct way with an aim to providing useful decision tools at completion. Finally, federal funding, while encouraging interdisciplinary research in many cases, is often still organized around scientific disciplinary themes, rather than broader cross-disciplinary issues and does not specifically promote systems science. Marshaling a multi-disciplinary team together does not necessarily mean that systems science principles will be applied.

Still, there are significant and genuine movements in the systems science direction. Issue-focused centers continue to proliferate at research institutions. They often have cross-college support and acknowledged validity from high-level administrators. Many institutions are also hiring new faculty at the interdisciplinary interfaces of several departments/colleges. This creates a more directed climate for cross-discipline interactions, rather than relying on happenstance collaborations among individual faculty. While the recent fiscal crises at many universities have forced departmental consolidations or eliminations, it has had the benefit of merging disciplinary departments that, otherwise, did not interact closely. Under such stressful and strained circumstances, however, it will likely take some time before meaningful collaborations develop, but innovative faculty will certainly see and embrace these new opportunities. Lastly, federal funding has begun to encourage systems science thinking. Three such programs are the Environmental Protection Agency's Collaborative Science & Technology Network for Sustainability, CSREES's Enhancing the Prosperity of Small Farms and Rural Agricultural Communities Program, and the National Science Foundation's Biocomplexity in the Environment Program. Movement toward sustainability via systems science and other paradigms has also been reported by the National Research Council.[15]

3.2. Scale issues

The idea of ecosystem *management* (i.e., actually managing an ecosystem) is unrealistic at best. We can only hope to increase our understanding of ecosystems, so that we can improve our management activities.[16] Because ecological patterns and processes change with respect to scale, we need to be very cognizant of scale in biological investigations.[17] For example, annual forest regeneration may fluctuate widely within a stand (due to soil conditions), or even a watershed, but may be quite stable when viewed at a regional level (subject, instead, to climatological variability). These scale differences are particularly important as we interpret results, draw conclusions, and make management recommendations. Many of the ideas and suggestions in the following paragraph are borrowed from an edited volume on ecological scale by Peterson and Parker.[18]

First, terminology has been inconsistent.[16,17] *Scale* refers to the physical or temporal dimensions of phenomena. *Level*, on the other hand, indicates position within a hierarchical organization, e.g., trophic level. Within any particular level, the same phenomenon (e.g., organism) can be observed at many different scales, which will greatly impact the patterns discerned and the processes examined.

Second, from a practical standpoint, we all readily accept that research questions need to be relatively narrowly defined to make them experimentally manageable. However, such simplifications should not overshadow the multi-dimensional nature of ecological entities and processes. Focusing on a single metric is a necessary investigative convenience, but researchers need to be cognizant of all aspects of the phenomena being studied. In particular, as one scales conclusions up or down, these companion dimensions can have huge impacts on the applicability of earlier conclusions.[16] Because changing scales can bring many other processes into play, those other dimensions may, then, come to dominate the originally studied and measured phenomenon metric, and render ineffectual the knowledge gain about that original entity.

Third, models of ecological processes often contain many components. Calibrating data are needed to parameterize each part of the model. Care must be taken as these components are integrated to ensure that the calibrating data represent the same scale. Otherwise, linked model components will combine biophysical processes in an ecologically nonsensical way. As separately developed models are linked together—a fairly common procedure—scale consistency becomes very important. The data and analysis procedures used to develop each model require careful examination to uncover any scale discrepancies.

Fourth, despite most ecological researchers' appreciation for scale, it is infrequently treated explicitly. For the benefit of other researchers, and particularly for managers, scientists need to clearly articulate their study's spatial and temporal scales of measurement[16] and indicate where dependencies exist in their measurements (e.g., scale-independent allometric relationships). If extrapolations are made to other scales, those transformations should be described, along with any implications for interpretation.

Finally, most researchers recognize the systems nature of ecological study. However, just as scale differences are not always treated cautiously, in many cases, neither are shifts in system focus. At the same time that one moves from one scale to another, one also changes systems. Because other processes operate at that new scale, that shift also reflects a transition to another system. Few ecological problems are solved when viewed within the locality of a single system. Rather a multiple-system or higher-level system view must be examined to display the full complexity and connectivity of an ecological problem—this can be seen in the scope of various research challenges listed above. This implies, then, that ecosystem models must encompass those various systems to be comprehensively descriptive and predictive.

4. RESEARCH IMPLICATIONS

A number of current shortcomings exist in our national R&D environment for sustainability science: short- and medium-term funding streams limit scientific capacity; scale issues and systems thinking bring challenges to our more traditional disciplinary alignments, reward systems, and research protocols; and researcher-stakeholder partnerships are largely lacking. Despite these difficulties, we are seeing the creation of a cadre of new sustainability sciences. They have names such as, ecological economics, environmental economics, industrial ecology, environmental geology, ecological engineering, eco-agriculture, and environmental law. These new "disciplines" have arisen at the interfaces of more traditional disciplines that interacted very little in the past. Such re-alignment of science is necessary if sustainability studies are to be treated seriously.

The new objective function for sustainability does not maximize productivity. The last century of agriculture has seen tremendous increases in product yield. While advances in biotechnology will enable niche crop production for overall productivity increases (e.g., drought-tolerant plants), further marginal yield increases will only be possible with ever-increasing inputs of chemicals and water. Even precision agriculture technologies will not increase field yields (perhaps even reduce yields slightly), but they will help to increase efficiency and lower inputs. What has not been widely recognized to date is the opportunity to increase agricultural services or amenities.[12] Agriculture can contribute significantly to carbon sequestration, biodiversity (both through habitat preservation and migratory corridor protection), recreation, green spaces, and water quality and quantity. Future biophysical and economic models need to include these benefits to accurately portray agriculture's contributions to societal values.

A thorough biophysical understanding of ecosystem processes can only provide a partial solution to any ecological problem. To translate that partial solution into something more complete will require that we embrace the full complement of socioeconomic systems as equally important aspects of the solution. In most cases, those same socioeconomic systems have been contributors to the problem, so likewise they need to be contributors to the solutions. To do that, however, will require that our scientific institutions acknowledge their responsibilities to educate, especially given the global contexts within which many sustainability problems reside.

Periodically, there are those who advocate modeling efforts that are designed to signal ecological problems before they occur—*anticipatory* research. However, little, if any, work proceeds along those lines. Most ecological models are not constructed with this intent in mind, and few researchers place sufficient confidence in their models to extrapolate to unrecognized problems. However, with proper attention to ecological scale combined with a system science approach to investigation, we will have the tools in place to conduct anticipatory research. Because we will be able to understand a system's dynamics and approach them at the appropriate scale(s), we will be positioned to make informed predictions about system behavior within an ecologically meaningful context. As our environmental problems become more complex and far-reaching, the ability to anticipate impacts (or understand them shortly after they are uncovered) will greatly improve our reaction time and inform our alternatives.

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