Sustainability

Douglas H. Fisher
Vanderbilt University

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Long-term planet sustainability, if to be realized, requires attention to global balances over vast time scales, which must expand our notions of scientific investigation. Sustainability cannot be about "fighting fires," a constant reaction to emergencies. How can we describe and prescribe the science and engineering enterprises over time-scales larger than decades? What is effective scientific leadership in the context of large time scales? Is charismatic, assured, fast-on-the-feet leadership, often so attractive in other contexts, a leadership style that will be conducive to long-term sustainability? Can leadership in the science of sustainability be separated from leadership in activism and citizenship? Is long-term sustainability so vast that individuals simply cannot be effective leaders over any significant time scales, or is leadership only meaningful at the level of governments, perhaps corporations, and other communities?

Questions of what should be sustained and what should be changed are best framed by background on what is actually changing. Foremost is that the climate is changing rapidly and the consequences are huge to many people even now, and potentially huge even to the wealthy of upcoming generations and others who might feel insulated against the changes. There are other changes to our environment, which while less prominent than climate change, are every bit as significant for human health, such as pollution and its possible links to diseases such as cancer. Moreover, activities such as limited recycling of materials, which many would regard as contributing to a sustainable planet, barely dent the threat of human consumerism to societal and environmental balances.

Science and Sustainability in Context

Sustainability has been succinctly expressed as meeting “the needs of the present without compromising the ability of future generations to meet their needs” (Brundtland 1987). This begs important questions that are rarely asked in common discourse. What are “the needs of the present,” and what are the needs of future generations -- are they the same needs or different? Is present-day consumerism in the materially-wealthy world overlooked by imagining enhanced abilities in the future to achieve “needs?” Do we imagine that in the future that avatars and virtual worlds will satisfy human needs for companionship and to play in nature? Perhaps we assume that humans will evolve differing needs, suitable to a different environment? Do we imagine that increased incidence of cancer and mental health problems, perhaps due to a toxic and congested environment, will be offset by medical breakthroughs? And who and what is “the present”? Is it the materially wealthy only? Is our view of sustainability so human centric that planet characteristics such as biodiversity are only valued to the extent that they contribute to humanity?

Sustainability interdependencies are complex (Strange and Bayley 2008), but *sustainability* is a term tossed around as though it’s meaning were self-evident; this is not the case. For example, some consider plans for natural catastrophes such as super volcano eruptions and asteroid strikes as part of the sustainability landscape, while others might not. Moreover, nuclear war, terror, and waste remain important sustainability concerns. Some of the biases, beliefs, and desires that result from our honest reflections on sustainability will differ. These differences, if properly acknowledged and managed are not only "ok" because they are human, but vital. Sustainability requires some notion of balance, and is it ever the case that a balanced community of humans is a community of individually balanced members? Balance in human communities stems from diversity of experience, skills, beliefs, and priorities. Does diversity raise collective intelligence, and what of the implications of lack of diversity, particularly of gender in certain scientific disciplines and most governments? The exclusion of women from the halls of power is among humanity's biggest failures, stemming from pathology or an inability of human evolution to stay on pace with technological change – gender imbalance is a lynchpin issue for a sustainable planet (OECD 2008).

It is often said that the rest of the world is waiting for the United States to *lead* on climate change. An alternate interpretation is that much of the world is waiting for the US to *follow*. In any case, "it is impossible to imagine a meaningful solution without America really stepping up" (Friedman 2008: 6). Generally, a robust world requires that those who lead in some circumstances must follow in others. Any theory of leadership that does not explicitly acknowledge this need to follow is a frail egocentric theory and ill-suited to the long-term sustainability of our planet.

In 1955, when an African-American woman named Rosa Parks refused to give her bus seat to a white passenger, she was a citizen asserting her right to equal treatment. However, she was also contributing to the wider Civil Rights Movement. As Paul Loeb

(1999: 35) says, "she was part of an existing broader effort to create change, at a time when success was far from certain. This in no way diminishes the power and historical importance of her refusal to give up her seat. But it does remind us that this tremendously consequential act might never have taken place without an immense amount of humble and frustrating work that she and others did earlier on." On time scales of importance in sustainability – decades, centuries, millennia – leadership is a characteristic of collective cognition and conation. Though we stand on the shoulders of giants, it is a safe bet we do not know most of their names.

Sustainability Leadership in Science

It is worth distinguishing leaders *in* science from leaders *of* science; the latter includes governments and corporations through the funds they provide for research. Another critical point is that science is not monolithic – there are many subdisciplines.

The National Science Foundation (NSF) in the United States carries a major responsibility for supporting fundamental scientific research that may provide the knowledge base for achieving sustainability (National Science Board 2009). By its own estimation, NSF is responsible for about 20 percent of the basic research science funding in the US. NSF Directorates covering the broadest scientific areas (Biological; Computer and Information Sciences; Educational; Engineering; Geosciences; Mathematical and Physical; Social, Behavioral and Economic) are decomposed further into divisions and below these are core programs. This organization gives stability and continuity on which US scientists and engineers can rely when they seek research funding.

Topics related to sustainability span NSF's core programs. The Biological (BIO) and Geosciences (GEO) Directorates are clearly related to understanding sustainability issues such as biodiversity and climate change. Because humans radically change ecosystems, the Social, Behavioral and Economic (SBE) Sciences are key to understanding and curbing destructive human behavior and promoting sustainable behavior. The Engineering (ENG) Directorate's relevance to sustainability is in how materials, chemicals and artifacts are designed, built, used, and reclaimed, ideally with energy efficiency and recycling in mind. Computer and Information Science and Engineering (CISE), as well as Mathematical and Physical Sciences (MPS) are key to understanding the complexity of an emerging sustainability science. The Education and Human Resources (EHR) directorate includes how understanding of sustainability can be taught and learned.

To complement the stability of the core programs, interdisciplinary (or crosscutting) programs involve multiple NSF units (directorates, divisions, programs), adding flexibility. These programs are created as NSF officials deem appropriate to promote emerging areas of science, and as such play an important leadership role. For example, the program on Dynamics of Coupled Natural and Human Systems (CNH) is a collaboration between the Directorates of Social, Behavioral and Economic Sciences; Biological Sciences; and Geological Sciences. The CNH program has persisted for 10 years and "promotes interdisciplinary analyses of relevant human and natural system processes and complex interactions among human and natural systems at diverse scales."

It is no accident that this example of NSF interdisciplinary programs has SBE as central --- because people are central to sustainability. Take something as straightforward as energy efficiency, usually the purview of ENG and CISE. As the "per-unit" energy efficiency of a system improves, people use more of such systems for more tasks, so that the collective energy use of the totality of the systems may go up! This is an example of a *rebound effect* (e.g., Jevons 1866: 8), an unanticipated consequence of a technology. Understanding and guarding against rebound effects is in the purview of a hybrid of social and technological sciences; NSF programs such as *Social-Computational Systems*, a pairing of CISE and SBE, herald this new, and for sustainability, all-important scientific discipline.

In 2010, NSF announced a number of across-directorate programs strongly focused on sustainability, including climate change education, biodiversity, computational and mathematical modeling of Earth processes, and ocean acidification. These programs followed behind a new US president, who was concerned with sustainability, notably climate change. While these programs are good news, they come almost 50 years after scientists became confident in rising atmospheric CO_2 and its implications for global temperature; while government is a leader of sustainability science, it is not always an effective leader. Nonetheless, the 2010 programs herald a proposed 2011 program – *Science, Engineering, and Education for Sustainability (SEES)* – at about 10% of the total NSF budget request.

The various sustainability programs are examples of how NSF nudges the scientific community towards *use-driven basic research* (Stokes 1997), where an application problem sparks a search for understanding that then proves more general than the motivating application. Complementing these top-down influences, are bottom-up influences on NSF from individual scientists and scientific bodies. Much of this influence is unstructured – scientists send in proposals, and then program directors (who are typically scientists themselves) identify themes across proposals, which then inform proposal reviewing and program creation.

While the SEES program and its immediate predecessors are new, NSF funding of researchers in sustainability has been going a long time. For example, Charles Keeling (1960), one of the earliest and respected proponents of CO_2 monitoring, received NSF awards between approximately 1959 through 2002 for this work.

At a very coarse level of *descriptive* (versus *prescriptive*) analysis, scientists lead by alerting government (and society) of phenomena like climate change; government leads by encouraging synthesis across phenomena and disciplines. It's a no-brainer that Geoscientists, followed closely by Bioscientists, would concern themselves with climate change. However, the relatively recent interest in climate change by scientists outside GEO and BIO is government driven to a considerable extent.

There are also structured bottom-up influences, where NSF proactively asks scientists to think deeply about research challenges in particular areas. The National Academies, which are not a government organization, brings ideas to NSF for funding as unsolicited proposals, but often NSF will solicit a proposal from the National Academies. For example, in 2008 at NSF's request The National Academy of Engineering (NAE) developed a list of Grand Challenges for engineering. Of the 14 NAE Grand Challenges, at least 7 are core sustainability issues: (1) Make solar energy economical, (2) Provide energy from fusion, (3) Develop carbon sequestration methods, (4) Manage the nitrogen cycle, (5) Provide access to clean water, (6) Restore and improve urban infrastructure, and (10) Prevent nuclear terror. Others, particularly those concerned with human health, are at most one step from core sustainability concerns.

NSF is unique among Federal agencies; its charge is very general, to fund basic research and education in all fields of science and engineering. Other nations have their own such agencies, such as the Japanese Society for the Promotion of Science (JSPS) and the European Science Foundation (ESF). In contrast, mission-oriented agencies in the US and elsewhere have constrained domains of oversight. Sustainability responsibilities are distributed across many agencies and the Cabinet-level departments (e.g., Interior, State, Agriculture, Health and Human Services, Energy) under which they fall. Sustainability relevant agencies include the Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA), U. S. Geological Survey (USGS), Forest Service (FS), National Institute of Standards and Technology (NIST), National Aeronautics and Space Agency (NASA), U. S. Agency for International Development (USAID), the U. S. Food and Drug Administration (FDA), and National Institutes of Health (NIH).

In addition to countries' national agencies and departments, international agencies and organizations abound. Some of the United Nations' sustainability focused agencies include the Division for Sustainable Development; the World Food Programme (WFP); the Food and Agriculture Organization (FAO); and inter-agency groups such as UN Oceans, UN Energy, and UN Water. With the World Meteorological Organization (WMO), the UN founded the Nobel-prize winning Intergovernmental Panel on Climate Change (IPCC), which assesses science on climate change and its consequences.

The Organisation for Economic Cooperation and Development (OECD) has over 30 member nations, compiles and analyzes comparative data to inform policy by its members. It is composed of Directorates on Environment; Science, Technology and Industry; Economics; Trade and Agriculture; and others. The OECD's horizontal (interdisciplinary, crosscutting) program on Sustainable Development covers areas ranging from climate change, agriculture, environmental indicators, biodiversity, and many others (e.g. OECD 2009).

There is great complexity in coordinating across agencies and across nations on sustainability. There is no Department of Sustainability in the US, nor most other countries, though such offices are sprouting up at regional and some national levels to manage the mammoth task of effective coordination (e.g., Germany's Federal Ministry for Environment, Nature Conservation and Nuclear Safety). There are other notable national efforts along some dimensions of sustainability, most notably energy and climate change (e.g., Denmark; South Korea). In addition, sustainability institutes and schools are emerging in Academia. For example, Arizona State University's School of Sustainability, established in 2007, has a comprehensive curriculum that includes water management, energy and materials, food systems, decision-making, policy and governance.

Living Beyond Our Means

Humans are radically changing the biosphere through technology. Our mental and physical capabilities enable us to borrow resources against the future, and commentators have long reflected on cavalier, unsustainable human consumption (e.g., Jevons, 1866);

as our numbers increase, the debt grows. This section surveys two broad phenomena that are manifestations of living beyond our means.

Climate Change

Currently staring us in the face is climate change, which Orr (2009) calls “the long emergency.” There is strong scientific consensus that the current changes are human-caused, stemming from the burning of fossil fuels like coal and oil, which release the greenhouse gas CO_2 into the atmosphere. The science of some of this, for example that CO_2 is a greenhouse gas, has been known for over a century. Moreover, the actual rising atmospheric CO_2 and rising temperature trends have been tracked for over 50 years (Weart, 2008).

Consider the following from a public policy text published some 20 years after scientific observations by Keeling and others of rising atmospheric CO_2: “The greatest potential risk, but also the most uncertain, is the effect of CO_2 from burning coal and oil… typical temperatures might rise as much as 3 degrees C (and considerably more near the poles)… These changes would probably occur slowly enough that we would have some warning and could perhaps act to mitigate the disaster...” (Barbour et al 1982: 99).

The current and projected consequences of increases in CO_2 (and other anthropogenic influences like aerosols) are many (Parry et al 2007), including increasing average global temperature; rising sea level from melting polar ice; an increase in the number and severity of extreme weather events; increased precipitation in some areas and increased drought in others; increased acidification of the oceans, negatively impacting sea life; uncertainties and variations in crop productivity; decreases in cold related deaths and increases in heat and malnutrition related deaths, particularly in developing countries.

Despite international efforts to reduce its release (OECD, 2009), human-added CO_2 into the atmosphere is growing. One reason for this continued growth is the growth of humanity itself; CO_2 emissions grow with population. Even if each person cut his or her CO_2 emissions by 1/2 (or by any "constant factor"), the amount of CO_2 produced would still grow at proportionally the same rate it was before the cuts; if it were exponential growth before, it would be exponential growth after, and within a relatively short number of years, we would return to the same absolute level of yearly emissions. There are several points worth making here. First, at least "constant factor" cuts in CO_2 emissions are critical if we are to substantially mitigate future climate change. Second, such cuts are not enough to halt climate change in the long run; for reasons already mentioned and because CO_2 accumulates in the atmosphere, leading to increasing accumulated CO_2 even if the amount of per-year CO_2 is decreasing. In contrast to constant-factor cuts, *mitigation* through alternative energy such as solar and wind, offer a possibility of reducing emissions to zero in some sectors.

Because it doesn't appear that we will reduce atmospheric CO_2 in the near future, there is increasing talk of *adaptation* to climate change (Parry et al, 2007). Smith (1997) distinguishes between *anticipatory* adaptations and *reactive* adaptations. Anticipatory adaptation is that which is planned, while reactive simply happens. Many natural adaptations are reactive, such as species migrating to regions with (new) climate to which they are better suited; communities' planned responses to these migrations would be anticipatory adaptations. Other examples of anticipatory adaptation include planning to relocate coastal populations, hardening civil infrastructure to better withstand extreme weather, design and distribution of low-cost water pumps for developing nations, and building low-energy housing to minimize the burden on the electrical grid. Fankhauser, Smith, and Tol (1999) conclude from an *expected cost* analysis that long-term infrastructure investments are best informed by climate change possibilities.

In addition to what many would regard as relatively benign methods of adaptation, *geoengineering* is the deliberate alteration of the environment through technology, and it is a particularly controversial means of adapting to climate change. Examples of geoengineering include seeding the oceans with iron to increase phytoplankton and therefore photosynthesis and carbon sequestration, and seeding the atmosphere with sulfur to reflect sunlight back into space, thereby lowering solar radiation that is warming the planet. Because seeding would need to be performed regularly, a huge concern is that if humankind did not mitigate and sequester CO_2, then the geoengineering intervention could not stop without immediately returning the climate to a catastrophic state.

There are ample lessons for sustainability generally by looking at the case study of climate change. Because climate change is a potential disaster in progress, Barbour et al (1982) suggested it may awaken a threatened civilization into action, possibly towards a sustainable future. Unfortunately, humanity may have to “hit bottom” first. The materially wealthy world’s need for fossil fuels has been likened to an addiction (Cokinos, 2010), though energy generally is probably the true addiction.

The failure to successfully mitigate; clinging to uncertainty as a reason for inaction; and increasing talk of adaptation with the risky behaviors of geoengineering; all seem consistent with an addict on the way down. In his essay "Prozac for the Planet," Christopher Cokinos (2010) suggests that radical geoengineering would be a prescription drug to substitute for fossil fuel dependence, though a drug that is far from "FDA approval." However, because of what we know of human procrastination, geoengineering might only enable continued addiction, paving the way for an even deeper bottom. The addiction metaphor suggests that we identify what it could mean to "hit bottom" for a society -- and what actions would be effective at those critical points.

Human Health

Another area in which humanity seems clearly *behind the emergency* is in links between environment and human health. Dan Agin points out that the "first environment" is the womb, and lays out the evidence that environmental toxins negatively impact the embryo and fetus, leading to deficits after birth and later in life. This is strikingly commonsensible, but Agin (2009:18) correctly qualifies: "Some people may complain that much of the evidence presented in this book suggests rather than demonstrates the neurological effects of negative impact, in or outside the womb, on the prenatal environment. That caveat is worthy and clear, but it's also clear that when a smoke alarm goes off in your house, suggesting a fire, the most prudent action is to find out what's happening."

Agin's fire alarm metaphor is apt, both with respect to the potential effects of toxins on human health, but also the effects of anthropogenic forcing of climate change. Another good metaphor reflecting this conservatism is that of a clinical trial: before it is concluded that the drug has a positive effect, a high confidence in the drug's benefit is established, but if patients start dying or exhibiting other extreme detrimental symptoms, clinicians stop and figure it out. In this latter case, the high cost to human health associated with the negative outcome offsets the lower level of confidence in the reasons for the outcomes.

What is so striking about Agin's need to qualify his survey is that it comes almost 50 years after the publication of Rachel Carson's (1962) *Silent Spring*, which laid out a strong case about toxic poisoning of the environment with strong biological consequences. Carson's book is widely regarded as the trigger of the modern environmental movement, though through no fault of Carson's, it's a movement that has waxed and waned in terms of government and public embrace.

Hilgenkamp (2005: 78-97) surveys the most prevalent toxins in the environment and their known or suspected effects on human health and in cancer particularly (NIH, 2003). Some influences are complex and subtle, for example insidious harm to child development that may not even be diagnosed with confidence, because the threshold levels of the toxins may be quite low (Stein et al 2002).

The Breast Cancer and the Environment Research Centers are a consequence of advocacy groups, scientists and government agencies coming together, looking at environmental influences on breast cancer (Parthasarathy, 2010; Baralt and McCormick, 2010); the dynamic of 'community-based participatory research' is instructive for citizen science and leadership of science generally.

Steps Towards Sustainability

Climate change and toxins are consequences of living beyond our means. One response to the latter problem is to eliminate human-made toxins from the planet, but as with anthropogenic forcing of climate, this seems unlikely in the short term. McDonough and Braungart (2002) advocate an intriguing strategy – the separation of technological cycles and biological cycles in the design and manufacture of products. The authors advocate non-toxic materials, but allow for some need (at least in short term) of toxic materials – the key is to insure that materials that do not biodegrade benignly are easily separable from those materials that do, so that each enters a separate recycling stream.

McDonough and Braungart's larger vision is a *cradle-to-cradle* (C2C) lifecycle in which products are *fully* recycled with *no degradation* in the constituent materials. C2C is a grand vision, motivated by goals for very long term sustainability, so that resources will not be depleted. McDonough and Braungart identify *monstrous hybrids* as products that combine biodegradable materials with those that are not so, in a way that they cannot be separated; at the end of the product's use, the hybrid is useless (or harmful) with respect to both the biological and technological cycles. A product as simple as a shoe can be a monstrous hybrid, if leather is tanned with a toxic solution.

Characterizing Consequences

To implement C2C, we need ways of formalizing consequences of different designs, of artifacts and societies. An ecological footprint (Wackernagel and Rees 1996), often informally used to convey some notion of environmental impact, is formally a measure of how much land (e.g., in acres) would be needed to sustain a person, community, nation, continent or planet *without degradation or permanent loss of resources*. The Global Footprint Network estimated that humanity, as a whole would require 1.5 Earths, which we don't have, to live sustainably if all current human activity remained at current levels.

Measuring the acreage of my house may seem straightforward (or of the buildings in my town), but how much acreage does my high-rise apartment count for, how much acreage is accounted for by the fact that I use a dishwasher instead of paper plates or that I take the train rather than drive a car? The mapping of many activities onto a common unit of land is an engaging exercise.

Energy footprints are often used alone, but are also a big part of any ecological footprint, where energy can be translated into acreage based on the source of energy; for example, the "land equivalent" of coal-generated energy is taken as the acreage of vegetative land cover needed to absorb (or sequester) the CO_2 produced through the burning of these fossil fuels.

McDonough and Braungart's cradle-to-cradle design is a clear strategy for minimizing humanity's ecological footprint. Climate change mitigation and adaptation can also be understood within the framework of ecological footprints. Mitigation is an orientation motivated by a desire to live within our means. Adaptation strategies like iron seeding the oceans can be viewed as motivated by increasing resources (the environment's sequestration capacity), but rebound effects of such interventions could reduce other resources. Other geoengineering strategies, like atmospheric seeding, would have the direct consequence of reducing energy from space and for flora, which relies directly on sunlight; for this and other reasons, there is fear that the intervention would lead to a faster, deeper bottom.

Formalizations, of which ecological footprints are an instance, open up studies of sustainability to computer scientists and mathematicians, groups we might not associate with sustainability. These groups have methods and technologies that are capable of grappling with the complexities of finding (near-)optimal solutions to complex sustainability problems. Related to this is that formalizations, perhaps counter intuitively, offer concise ways of communicating through various interfaces and visualizations with the public (to include scientists) and policy makers. Carbon calculators proliferate on the Web, are good examples of this possibility, but unexplained variances across these packages need to be better explained (Padgett et al 2008), which in turn might inform better devices for public communication (Ross et al 2010).

Finally, in performing an ecological footprint analysis it is typically vital that it is a *lifecycle analysis*, not just looking at the footprint of (say) your laptop while you own it, but how much energy went into its manufacture (perhaps to include the mining of the metals used to build it), and the land and energy implications of its disposal.

Rational Decision-Making

In the 1980s the evidence for global warming was growing, and long-known theory on greenhouse gases pointed to human activity, but because Earth is a complex system there was much uncertainty about the precision of specific projections such as 3 degrees Celsius (i.e., 5.4 degrees Fahrenheit) on global averages, and certainly on regional changes. Uncertainty by itself does not invite inaction; as suggested by the clinical trials metaphor, rational decision-making is guided by consideration of both probabilities and costs (Schneider, 1989; Schneider et al 2002).

Being informed on costs and probabilities is typically very challenging. In discussing agricultural production in particular, but complexity more generally, Wendell Berry characterizes good solutions to complex problems as those informed by larger patterns, leaving open alternative courses of action. In contrast, bad solutions optimize on a single dimension, often achieving "stupendous increases in production at exorbitant biological and social costs … "; the latter because the solution "acts destructively on the larger patterns in which it is contained" (Berry, 1981).

A small team of experts overseeing a clinical trial is in a position to weigh the probabilities and costs in a clinical trial, making a *rational*, *informed* and *timely* decision that maximizes the efficacy of continuing the trial or pausing and reassessing. In contrast, making rational collective decisions that weigh probabilities and costs is much more difficult with a population as varied in opinion as the US public, though scientific assessments have been provided at regular intervals by the IPCC and others (Parry et al., 2007).

Recent surveys indicate six reasonably well defined clusters of opinion in the US population, presumably comparable to the range of opinions in other nations even if the percentages holding each view differ (Leiserowitz 2010). The *alarmed* group has the highest belief in global warming, most concern over its consequences, and is most motivated to take action. At the other end of the spectrum are the *dismissive*s with opposite sentiments along belief, concern, and motivation. Comparison between two surveys, the first done in November 2008 and the second in January 2010, showed that the alarmed group declined from an estimated 18 percent to 10 percent, while the dismissive group gained from 7 percent to 16 percent. One plausible explanation is that record snowstorms in the winter 2009-2010 caused many to question the reality of global warming.

There is much relevance for leadership here; several findings, including the public's perception that scientists disagree "a lot" on climate change is symptomatic of a communication breakdown. The fault is not just with scientists, but many scientists do not prioritize highly the communication of their science to the larger public. Funding agencies can encourage with incentives or require that (balanced) research teams include expertise in communicating science to the public.

Additionally, the variance of belief across the groups and the ease with which group proportions shift, all speak to the difficulty of collective decision making regarding climate change and sustainability generally.

Even when human decision-making is rational, it is often shortsighted. In large part this is because people *discount* the future, placing much more importance on the present than the future. Behavioral scientists have explored different forms of human discounting (e.g., Steinberg et al 2009), to include "future orientation" and its relationship to sustainable behavior. Though constrained by the past, the future is large (Bossel, 1998), and projecting scenarios very far into it adds great complexity to any decision making task; discounting is likely an evolutionary adaptation that limits complexity, but in the presence of transformational technology it is a maladaptation.

Information and Communication Technology

Computer science offers tools to deal with the complexities of sustainability in the face of population growth and transformational technology. However, we should doubt technological magic bullets *of any kind* would fix our unsustainable behavior. There was a time we thought we could send our population overage along with our waste into space – that technological fix isn't going to happen soon, though the challenges of space travel did advance sustainability-relevant technology, and inspire a spirit of environmentalism through pictures of Earth against the backdrop of space.

The collective direct footprint of information and communication technology (ICT), from design and manufacture, lifetime use, and disposal -- is measurable in terms of energy requirements, resource/material depletion and waste. The most highly visible efforts are in reducing the energy required for individual computers. These efforts are not conscious of rebound effects that result in a rise in the collective energy footprint across all computers worldwide, overwhelming the per unit improvements. Rebound effects are not specific to computing but ubiquitous: "it is only when it is understood that our agricultural dilemma is characteristic not of our agriculture but of our time that we can begin to understand why these surprises happen, and to work out standards of judgment that may prevent them" (Berry, 1981).

Another issue is the interaction between sustainability factors in ICT (Kohler and Erdmann, 2004). The promise of computing to reduce energy in other sectors is vast, perhaps co-extensive with energy-hungry applications themselves. But as Berry warns, optimizing on a single dimension, in this case energy, to the exclusion of others is dangerously short sighted. The concept of cradle-to-cradle design is badly needed in the ICT sector. For example, promoting pervasive computing without attending to the implications for disposal, recycling and resource depletion is naïve, myopic and irresponsible; though the behavior seems symptomatic of the field, and many other enterprises in the materially hungry world. It remains an open, but obvious question – does designing for energy efficiency, which often means specialized hardware, make recycling more difficult? It would be prudent that research programs that are focused on energy efficiency, couple this with attention to anticipating and designing against detrimental rebound effects; even if individual researchers in technology are not adept at studying such secondary effects, agencies like NSF are masters at encouraging the balanced, interdisciplinary research teams that are. Broadly, an integration of the social and technological sciences, to focus on predicting and preventing rebound effects of technology, is badly needed; government needs to create incentives for this science to form and grow.

The promise of ICT is that their application in other sectors will effectively address larger problems of sustainability (Tomlinson 2010). These indirect benefits of ICT include monitoring and planning to protect biodiversity; climate and ocean modeling, and intelligent decision making tools to inform policy making. In addition to reducing the direct energy use of the computing sector, the application of computing to reduce energy use in other sectors is oft discussed, to include intelligent control of appliances on smart electrical grids, energy monitoring to inform consumer energy use, obviating (energy for) travel due to virtual and collaborative work environments or optimizing travel routing to reduce energy use.

At present, much of ICT's promise is theoretical and not practiced. An example of low hanging fruit that is not sufficiently picked is ICT's ability to substitute for travel. For example, NSF asks reviewers of submitted proposals to come to NSF from across the nation and the world, contributing a sizable ecological footprint. But NSF and other organizations could take substantive steps to implement the use of ICT instead of travel, and scientists could encourage it. Society, to include scientists, must start taking the environment into account as a factor in defining the optimality of all our processes if we are to have any shot at a sustainable planet with good quality of life for its inhabitants.

While failure to snag low hanging fruit with ICT is disappointing, computer researchers are substantively addressing high hanging fruit. A new field of *computational sustainability* is emerging, led by several people including Carla Gomes, director of the Institute for Computational Stability at Cornell University, which is using computational and mathematical formalisms to reason about characterizing, monitoring, and protecting biodiversity, among other sustainability-related problems (Gomes 2009). An example of the biodiversity research includes determining "optimal" policies for acquiring habitat, through purchases of private land, for the grizzly bear and other species (i.e., so-called "reserve design"); this problem will only become more complicated as the climate changes and species migrate in response. This is but one example of moving targets in ecological research that makes computational and mathematical tools for analysis so important for handling complexity. Besides the dynamic nature of ecologies, uncertainty in observations (e.g., the number bears that are in a region, given an exact count is impossible), and competing interests (e.g., the bear's, the rancher's, the tourist's, the native American's, the salmon's) as expressed by multi-objective functions, all make biodiversity questions complex.

Human decision makers may ignore facts because they are simply overwhelmed by complexity. In *Soul of a Citizen*, Paul Loeb echoes Berry that good solutions must be integrated into a larger whole, saying, "We can contribute to the well-being of our society, the body politic, by applying a similarly holistic ethic of interdependence, and by listening to those whose voices are too often excluded from public discussion" (Loeb 1999:131). Balancing the many voices is one aspect of what Computational Sustainability is about. Another part of the problem is actually hearing those voices, and sensor networks and online social networking can be a big part of that effort (again, with attention to recycling). While social networking has enabled easy community fragmentation, tools are coming online that are encouraging community coalescence. This is a humanistic possibility of computing, as a bridge between science and citizenship.

Conclusion

The sustainability landscape is vast (Conklin, 2006; Bossel, 1998). This essay has been selective, barely mentioning vital areas such as alternative energy, food processes and water. The emphasis has been on thinking, and failures thereof. Two entreaties run throughout the essay -- that we take seriously rebound effects of technology, which are both pervasive and consequential; and we grow socio-technical sciences that anticipate, evaluate and design cognizant of rebound effects.

The essay concludes with two (of many) systemic factors that impede long-term collective cognition and conation relative to sustainability.

Lack of diversity: Women are vastly underutilized, and the negative consequences for long-term sustainability are dire. When women gain equal rights, there are improvements in economy and environment. Even in nations where women have overt rights, the numbers of women in government and other positions of power such as corporate boards remain exceedingly low. In the United States for example, OECD (2008) reports that only 15 percent of legislators are women, ranking 22/30 OECD countries surveyed. At time of writing 17/100 US Senators are women, more than ever and reason for excitement, but excitement that itself highlights the pathological extent of the imbalance – 17 percent ! The dearth of women in positions of power, to include Academia, only passes for normal because it is so pervasive. Women support sustainable, lower footprint consumption in greater numbers than men, and the report says women "give greater emphasis to social welfare, legal protection and transparency in government and business" (OECD 2008:61). How would government operate differently, both in form and substance, than it does now with an equality of women? A paucity of women is also found in some science and many engineering disciplines. That women are not more fully participating in directing development of disruptive technology does not bode well for planet sustainability.

Segregation of science and its broader impacts: Many engineers and scientists do not put much thought into the broader impacts of their science, to include rebound effects. The reasons could be several. Consider that Technology and Society classes are often designed for non-majors and majors alike, coming near the beginning of the curriculum. While intended to attract students to science, these courses may also convey a second-class status to the “broader impacts” of science and engineering, and model compartmentalization in our curriculum – “we’ll talk technical material in here, you’ll see how it relates to society over there.” There are also few textbooks in the technology area that even attempt to fold contemporary issues into the science, though a notable exception is the Patterson and Hennessey (2009) text on *Computer Organization*, where contemporary issues, to include sustainability related applications, are given substantive treatment. Leadership in the integration of technical and societal material is coming from individual scientists, government agencies, and accrediting bodies like the Accreditation Board for Engineering and Technology (ABET). Importantly, there is evidence that better integration of technology and its broader impacts may induce more women into technical fields, thus linking two factors that are crucial for greater attention to sustainability.

Even if individuals don’t feel empowered to address sustainability per se, these systemic issues can be priorities that will advance a sustainability agenda.

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