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EDITORIAL

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Higher education: the quest for the sustainable campus

I was confronted with a profound dilemma as an undergraduate engineering student at the University of New South Wales in Australia in 1992. I had been taught that our planetary life-support systems were in a state of alarming decline by an institution that operated as if what the faculty was teaching was irrelevant. Lights were left on in empty overcooled classrooms, recycling bins were nonexistent, lawns were maintained using pesticides and herbicides, diesel trucks spewed fumes as they passed on their way to drop off chlorine-bleached virgin paper. This disconnect was very alarming to me. While it was obvious that universities should play a leading role in teaching and researching sustainability issues, I wondered how it could be possible to make widespread institutional changes to meet the demands of environmental sustainability when it was not even being done in the very university sector where these ideas were being promulgated. If universities would not change, then who can and who will, I wondered? To a growing number of people, the idea of teaching sustainability without demonstrating it is highly problematic. It is also widely believed that the ability of the higher education sector to reform its own practices is an important indicator of humankind's ability to address the global environmental imperative across all sectors of society. These sentiments have helped fuel what is now referred to as the campus sustainability movement, a movement dedicated to transforming our campuses into living laboratories for the demonstration and practice of environmental sustainability.

I have participated in this movement over the last 18 years, working with dozens of different universities around the world as a campus sustainability professional and as a member of a variety of related professional networks, as well as a lecturer in change management for sustainability. In 2000, I was recruited to found and direct Harvard University's Green Campus Initiative (now the Office for Sustainability).[1] Over a nine-year period, I teamed up with a large number of talented people across the institution, including my former academic and administrative co-chairs, Professor Jack Spengler and Tom Vautin, and together we worked to grow this initiative into the world's largest green campus organization, and one of the most influential. Harvard received the highest green campus ranking in such 2008 publications as the Princeton Review Green Rating Honor Role, the Sustainable Endowment Institute Green Report Card, and the Sierra Club Top 10 Green Schools. What we experienced and discovered in this fertile period in arguably the most complex, decentralized, and politically charged campus in the world, warrants much reflection. With this in mind, I recently resigned from my role as director to open up time to write, teach, and reflect with others to gain a better understanding of the many challenges and opportunities that lie ahead in the now thriving campus sustainability movement. It is my hope that sharing some of these thoughts, in their early stages, may help motivate related discussions and further exploration.

The campus sustainability movement emerged in the early 1990s and has since gone through two evolutionary waves. The first was spent envisioning and articulating the need for campuses to incorporate all sorts of innovations to reduce overall environmental impacts. We imagined campuses filled with green buildings, renewable energy systems, local organic food, organic landscaping, enriched native biodiversity, low-pollution transportation systems, bicycle paths, onsite rainwater-storage tanks, grey and black water-treatment systems, socially invested endowments, green chemistry practices, zero solid waste laboratories, green cleaning products, and low greenhouse gas (GHG) emitting campus utilities, along with many more ideas.

Throughout the 1990s and early into the new millennium, campuses around the world experimented with various green campus projects, and we can now find examples of almost everything on the green campus wish list. However, along the way some of us started to notice that while universities were amassing project successes in a piecemeal fashion, they were not achieving the kind of deep organizational transformation many of us now see as fun-

[1] See http://www.green.harvard.edu.

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damentally necessary (Sharp, 2002). For example, it was not uncommon for an institution to construct a showcase green building project one year only to revert to conventional building design in later projects. The single success had not actually reformed the building approval and design *processes* within the institution. Some universities would publicize specific energy conservation projects such as lighting retrofits one year while adding air conditioning to those same buildings the following year. These universities were achieving project successes without institutionalizing energy-intensity requirements to place limits on the energy used per square foot. Other universities placed grandiose and expensive recycling bins in public places while allowing waste generation to escalate, creating an isolated success with no comprehensive waste-reduction plan.

In recognition of the need to go beyond showcase-project successes, sometime around 2003–2004 the movement entered its second wave, applying more pressure and pushing for larger public commitments, dedicated staffing investments, and some kind of specific sustainability governance structure, typically in the form of a university committee with staff, student, and faculty representation. These efforts were aimed at moving the university sector beyond the little victories of single projects, toward sustained progress aimed at reaching larger environmental goals, supported by a professional capacity that could ensure ongoing progress. During this period, some important groundwork was laid in a relatively short timeframe, both in the United States and abroad. According to a National Wildlife Federation Campus Ecology Survey (NWF Survey) conducted in both 2001 and 2008, 65% of the 1,068 schools that responded in 2008 had some form of written commitment to address environmental sustainability or stewardship (or at least had a plan in place to create one), compared to 43% of the respondents in 2001. The 2008 data also showed that about 50% of participating institutions had sustainability committees in place and 51% "have staff or administrators responsible for leading sustainability issues" (NWF, 2008). Fewer than 2% of the schools surveyed in 2001 had sustainability committees and almost three-quarters of the new campus sustainability positions were created since 2003–2004.

In 2007, the American higher education sector had approximately 285 construction projects underway that had been certified under the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) program (USGBC, 2007). At the time, this accounted for about 10% of LEED projects nationally. In 2009, Recyclemania, the most popular campus-recycling competition in the country, had 500 universities competing, and the winning campus achieved a very impressive 78% recycling rate.[2] According to the association for the Advancement of Sustainability in Higher Education (AASHE), between mid-2007 and March 2009, over 620 presidents of colleges and universities in the United States endorsed the American College and University Presidents Climate Commitment (ACUPCC) that obliges signatories to achieve climate neutrality within a timeframe of their own choosing.[3] This pledge will require these educational institutions to avoid additional GHG's that may result from future growth, to reduce GHG emissions from existing operations, and to mitigate any remaining emissions by investing in carbon offsets, offsite renewable energy projects, and other measures. Collectively, these colleges and universities represent over 30% of the United States' student body.

The latest NWF Survey also showed that staff, faculty, and student-advocacy groups have been equal champions of the movement, debunking a common misconception that it was primarily student driven. Faculty have stepped up to participate in new governance structures to oversee ongoing efforts; students have continued to press for greater commitments; and staff members have worked hard to prove the cost effectiveness of a variety of initiatives.

Throughout the 1990s and up until fairly recently, the view of colleges and universities was that greening their campuses would simply cost too much, taking precious funds away from teaching and research. It is only recently that our institutions are finally realizing that an enormous amount can be achieved either at no added cost or within a very reasonable payback period. It took around five years for my team to change the prevailing mindset at Harvard University, resulting in a sea change in the level of participation across the campus. We reformed age-old assumptions by implementing a slew of cost effective building projects, purchasing changes, and behavior-change programs that generated over US$6 million a year in energy and waste reduction-related savings. Harvard University was not the only institution learning this lesson. The 2001 NWF Survey showed that only 9% of respondent schools said that cost effectiveness was a driver in implementing initiatives, but by 2008 the figure had risen to 24%. This represents an important shift away from the paralyzing assumption that greening the campus costs too much and does not generate any financial return. This shift has been especially critical in sustaining green campus activities during this challenging economic downturn.

[2] See http://www.recyclemania.org.
[3] See http://www.presidentsclimatecommitment.org/html/commitment.php.

While the movement's first and second waves have been key stepping-stones, they have not produced the breadth, depth, and pace of change that is necessary. Most global environmental problems are escalating at an exponential rate, and despite the last fifteen years of effort, the campus sustainability movement has not yet succeeded in achieving wide-scale transformation of college and university campuses into models of sustainable practice. To increase its effectiveness, the campus sustainability movement must now turn toward organizational change management, basing its strategies on a much more sophisticated understanding about how universities (and other large organizations) actually function so we can begin to unearth the enormous opportunities for increased innovation and transformation, adopting a systems-thinking perspective to steer an effective course forward.

Perhaps the most important legacy of the movement to date is the discovery that universities (and most large organizations) operate with a substantial degree of unconscious habit and irrationality and that very few people, at even the most senior levels, actually know how they truly function. This is in part the result of the compartmentalization inherent to large hierarchical organizations. The separation of different disciplines, arenas of responsibility, and tiers of management generally prevent people from understanding the broader context or the overall systems that operate across the institution. The fact that few individuals understand the broader institutional context, its systems and behaviors, has dire consequences for our efforts to navigate toward sustainability. This is because the demands of sustainability are system-wide and involve changing organizational culture, behaviors and the entire institutional context.

Despite our best efforts, experience shows us that planning and decision making are not always rational, and policy implementation does not necessarily follow a logically cohesive pattern that is consistent over time. Moreover, at times the components of the institution do not behave or interact in a predictable or even understandable manner. Compartmentalization, territorialism, complexity, risk aversion, and hidden drivers, to name just a few such dynamics, sometimes conspire to undermine even the most sensible ideas. Despite this, the institution depends upon its ability to appear more rational and self-aware than it sometimes is. I believe that there is a deep institutional culture of denial at play to sustain a myth of rationality, which in turn prevents us from engaging in the depth of institutional analysis necessary for navigating toward sustainability.

So far, the campus sustainability movement has been catering to the ideal of organizational rationality, writing up sustainability master plans, establishing new goals and indicators, adopting annual environmental reporting requirements, and so forth, as if there is a purely rational, conscious organization to take them up. Meanwhile, no attention is being directed toward the more complex, irrational, and unconscious life of the institution, allowing it to lurk under the surface as an ever-present threat to progress. To be clear, I am not advocating that rational planning and management processes do not have a critical role to play, just that they must be supplemented with a more sophisticated approach that works to diagnose and reform the very nature of our organizations. This effort must address everything from governance structures and decision-making processes, change management, finance and accounting practices, hidden institutional drivers and compartmentalization, engagement, capacity building, systems thinking and leadership.

New governance models and decision-making processes must be created to enable effective interdepartmental, interdisciplinary, and multitier engagement in the campus sustainability enterprise. At the executive level of our institutions we need a distributed model of ownership, accountability, and control that would bring vice presidents of finance, human resources, facilities, development, government and community relations, academics, and other departments into a shared state of responsibility and collaboration. Currently, universities do not do well with interdepartmental and interdisciplinary decision-making processes because, for one thing, their success depends upon transcending institutionalized habits of territorialism involving powerful personalities and significant complexity. Instead of addressing these challenges we commonly see our organizations structure the responsibility and leadership for sustainability under just one group or department. In the long term this can create a variety of undesirable tensions and issues resulting from a lack of effective coordination and integration. Developing new governance structures and decision-making processes that distribute and coordinate ownership and responsibility for the campus sustainability agenda requires the leadership of university presidents and other senior executives.

One way our educational institutions can greatly advance their campus sustainability efforts is to better comprehend the emerging role of the campus sustainability professional. The work of enabling the entire university to achieve continuous progress toward sustainability is a professional function not yet well understood. The typical university today might consider employing just one person to coordinate, communicate, and project manage sustainability across the entire campus, generally someone with no change-management skills, structured to report up through the facilities department. Despite their best efforts, passion, and commitment, most of these professionals are quickly overburdened and are without the skills, structure, or staffing level to achieve the necessary broad-reaching institutional engagement and transformation. What we are just starting to realize is that our organizations need to make a sizable staffing investment in a change-management function to drive organization-wide progress toward sustainability. The organizations that make this investment are able to achieve remarkable efficiencies and improvements right across the campus, producing financial and organizational returns that exceed the required investment. Without properly staffing and structuring this important change-management function, even the most progressive universities may become bogged down in a variety of destabilizing factors—political, financial, human resource, technological, or otherwise.

What does this sustainability change-management function look like and what does it do? To use the analogy of the large ship, this change-management function, in the form of a team of dedicated professionals, acts as "the rudder on the rudder," engaging a critical mass of the university community to steer itself toward a new course. The central role of the sustainability change-management team must be as a resource and catalyst to ignite people right across the university, to take initiative in everything from green building design and operations, renewable energy, environmental purchasing, recycling and waste reduction, green cleaning, alternative fuels, green office practices, green laboratory practices, organic landscaping, and GHG reduction. The structure and skill set of this change-management team must be appropriate for fostering engagement, capacity building, leadership, ownership, communications, and continuous improvement across the entire institution at all levels of management. It needs to have a very senior reporting relationship within the organization, reporting to the President or next in command to ensure legitimacy and enable access to all groups across the institution.

Over many years, I have observed that the common belief that people are innately adverse to change is not generally true. People are not resistant to change, they are opposed to instability, and they simply assume that change equals instability. When people experience stable processes of change they generally thrive on the experience and will readily embrace more change. Furthermore, by having enough positive change experiences, people often undergo a personal transformation, shifting from being passive participants to becoming leading agents of ongoing innovation and continuous improvement in the organization. For this reason, fostering stability during the organizational change process is a key function of the sustainability change-management team because it enables an organization to establish a culture of stable innovation and transformation across the campus. To achieve this stability, the change-management team must be able to engage in sophisticated ongoing institutional diagnostics, creative problem solving and pre-emptive action to address a wide variety of real or perceived risks and barriers. Sources of potential instability that may need to be diagnosed and addressed can include fears of negative reputational impacts, financial approval limitations, managerial backlash, capacity gaps, time pressures, and technological failures, among others.

At Harvard University, I needed to build a sustainability change-management team of 24 full-time campus sustainability professionals to carry the enormous workload associated with supporting wide-scale engagement, ownership, and leadership across a very decentralized, complex, and politicized campus of 40,000 staff, faculty, and students. Our funding model included a 20% contribution to our overall budget from the President's and Provost's Offices. The rest of our annual funding was sourced through an entrepreneurial business model that targeted a variety of projects and programs that generated ample savings from reduced energy and waste costs (over US$6 million per year after six years of work) which in turn was used to justify ongoing investments in our sustainability change-management team. I started small and grew the team and the related number of projects at an average rate of 30% each year for eight years.

Our institutions freely use the mantra of the "business case" to challenge and scrutinize the viability of anything new without addressing the fact that in many cases the business case is being sabotaged by poorly designed finance and accounting structures. Colleges and universities are incurring enormous additional costs by failing to reform these practices to enable good business practice to flourish. For example, institutional accounting structures separate capital budget management and operating budget management, and they rarely allow for operational savings to be captured and reinvested. It is not clear how this has evolved, but it occurs in almost all large organizations. This division results in capital budget managers resisting the expenditure of any extra money, even when the operation savings are extraordinary. At the same time, the operating budget managers commonly do not have enough access to funds for ongoing efficiency improvements. Even if operating managers do manage to fund efficiency improvements to produce operational savings, they are rarely allowed to capture and reinvest these savings for further improvements. Instead, they will often see next year's operating funds reduced to reflect this operating cost reduction, hardly a reward for a job well done.

The pathway to campus sustainability requires ongoing piloting and experimentation. Operational savings (costs avoided) can be an ideal source of capital for these pioneering activities. Experience shows us that the first time we do something new, it generally takes more time and costs more money, but that through repetition, time and costs are often reduced by streamlining processes and improving capacities. After some repetition we come to understand the true recurring costs and savings associated with the new activity, to the point of being able to budget accurately. I saw this process at work many times at Harvard, but perhaps the most compelling example was in relation to our green building efforts. When we first started to use the USGBC's LEED green building standard in 2001, we were told by many architects and engineers that we could expect to pay 5–10% more for our buildings. After five years of piloting LEED projects across the university, building internal capacities, and streamlining the overall process, Harvard was able to achieve its first LEED platinum renovation, the highest possible green building rating, at no added cost to the project. Other LEED Silver or Gold projects on campus were down to less than 1% additional cost with payback periods of eight years. To get to this point of efficiency, we had to first invest in the piloting and learning process. Unfortunately, most institutions do a very poor job of allocating annual funds for pilot projects and valuing the related learning processes. Others expend their resources on external consultants only to be left without any internal capacity for streamlining and embedding new practices. Because of this tendency, innovation, efficiency gains, and continuous improvement in general, are sporadic at best. Capturing and reinvesting potential energy and waste savings into future pilot projects and in internal capacity building are ways organizations can stimulate new levels of innovation without drawing down funds from other areas of the university.

At Harvard, we worked to overcome many of these finance and accounting impediments by implementing a US$12 million revolving loan fund that was available to anyone with a conservation project that could achieve a payback period of five years or less. Within seven years, building and facilities staff had borrowed over US$8.5 million to fund over 200 projects, including lighting upgrades; heating, ventilation, and air conditioning (HVAC) improvements; building-commissioning projects; and occupant behavioral change programs (encouraging people to switch equipment off, recycle more, and generally do their part). The average payback period for the first 200 projects we funded was just three years. Over time, I worked to broaden the scope of the Green Campus Loan Fund to fund feasibility studies, investments in metering, onsite renewable energy projects, and innovation in renovation and construction projects. To approve proposals, we established an advisory committee of facility managers that met each month to review applications. The revolving loan-fund model is clearly a successful strategy that many organizations have since replicated. However, the deeper lesson is that we should stop creating the ongoing need for revolving loan funds—by structurally connecting capital and operating budgets and institutionalizing life-cycle costing, a well-established methodology for calculating upfront and future operating costs relating to different decision-making options. I also believe that our organizations should capture and reinvest savings that result from successful resource conservation and waste-reduction efforts as routine practice to fund dedicated annual innovation budgets for financing pilot projects and ongoing efficiency upgrades. These are necessary next steps to enable the kind of good business practices, innovation, and continuous improvement our institutions need.

Beyond the finance and accounting arena, a variety of other hidden institutional drivers also exist within our organizations, posing a danger to all sorts of well-intentioned efforts. For example, some educational institutions engage in energy-purchasing contracts based on volume consumption. Under the terms of such arrangements, if the institution consumes less power, the unit price goes up, a disincentive for pursuing aggressive conservation. Others operate central utility plants (producing steam, chilled water, or electricity) that employ a business model dependent upon keeping as many people using their services as possible. They have a basic operating cost for maintaining infrastructure and staffing that is separate from the cost of fuel consumed. This base operating cost can be up to 50% or more of the energy bill received by the customer. Under this arrangement, any effort to remove a building from this central service to use an onsite renewable energy system like solar thermal or ground source heat pumps, for example, is likely to encounter resistance from the campus-utility team. This is because if they lose any of their campus customers, they have to pass on more of the base operating cost to their remaining users, which in turn can lead to a cascading loss of customers. At one campus I am familiar with, the steam plant used a condensate return-metering system that discouraged some building managers from repairing steam traps that had blown open. A blown steam trap wastes large amounts of steam and reduces the condensate that returns to the plant, resulting in a lower heating bill for the building. The cost of the wasted energy gets distributed across all bill payers as a "general line loss" fee. If the building managers were to spend money to fix their own steam traps, the extra condensate return would result in a higher bill for them and a slight reduction for everyone else, hardly an ideal financial incentive structure. In these cases, and many more just like them, the institution is actually incentivizing particular individuals, groups, or components of the broader system to optimize their own particular outcomes regardless of the overall system inefficiencies. To date, our universities have been slow to identify the existence of such underlying drivers. Going forward, we clearly need to actively diagnose the larger systems at play in our organizations, including the more submerged and complex dimensions.

Just as our organizations may be harboring submerged drivers that can effectively sink innovation efforts, individuals may also be harboring attitudes and feelings that can impede real engagement and learning. In many organizations a culture of private disengagement has taken hold in certain campus populations, typically as a response to a lack of bottom–up consultation or general engagement regarding everything from budget development, training, and advancement processes to operational decisions. Because of this feeling of exclusion, I have noticed there is often a systematic lowering of expectations and a withdrawal of creative energies and self-initiative from the workplace. People put their heads down, do their jobs, and nothing more. Some common sentiments are, "I've had ideas for how we could improve things for years, but no one listens and so I don't bring it up any more," or "They put this new system in but no one knows how to maintain it properly," or "No one's ever explained the bigger picture to me before so I've never thought about it." For any organization that is serious about making real progress toward becoming environmentally sustainable, having a culture in which these sentiments have taken root presents a profound impediment.

People are our greatest resource and, because the pathway to campus sustainability requires such wide sweeping and ongoing innovation and continuous improvement, our institutions must become learning organizations with the vast majority of people working in a state of public engagement and life-long learning. Most organizations have a long way to go before their community has evolved to this point. One of the most effective ways to foster engagement and learning across our institutions is through the use of peer-to-peer forums. During my time at Harvard, we experimented with dozens of different peer-to-peer models, working with building operations staff, kitchen personnel, residential students, facility managers, executive level managers, laboratory users, administrative staff, and more. We consistently found that structuring peers of the same social or professional group or managerial tier to engage with one another in a shared process of discovery, competition, teaching, and learning was extremely effective in tapping unprecedented effort and stimulating real learning. Peer-to-peer models of engagement are more costly to coordinate, but they produce savings well in excess of the investment, and they far outperform the common approach of having the "expert" or "authority" simply tell people what to do.

The basis of this success is tapping into innate human cognitive drivers and tendencies, something our organizations often fail to do. Cognitive research shows that approximately 95% of what we do is unconscious and the brain is constantly working to free up its 5% of conscious reserves by converting new behaviors into unconscious habit as quickly as possible (see, e.g., Bargh & Chartrand, 1999). In the institutional context, there is fierce competition for these conscious reserves, and often the process of developing new habits needs ongoing support. By creating an ongoing learning forum in which people are socially engaged with a group that they identify with and interact with frequently, we address two key learning challenges—attention and habit conversion. I now believe that connectivity between similar management tiers is just as important as the connectivity that exists up and down the chain of command. That is to say, horizontal flows of information, influence, and engagement are as important as vertical flows. This works at the very senior levels of our institutions right down the chain of command. When people ask how 620 university presidents across the United States publicly agreed to achieve climate neutrality, my answer is through the very skillful use of peer-to-peer influence. Once several presidents signed, advocates successfully leveraged this circumstance to catalyze others to do so, capitalizing on either a feeling of confidence in joining with others or a sense of risk in being left behind if they did not sign up.

So far I have talked about a number of ways in which we can achieve a new level of innovation and transformation toward campus sustainability. What remains to be discussed is how we can steer our course of innovation and transformation forward. Herein lies perhaps our greatest challenge, the task of adopting a systems-thinking approach to continuously diagnose and determine our path forward. Without taking a systems-thinking approach, universities may end up achieving significant progress in one environmental impact area while inadvertently increasing impacts on other planetary life-support systems. For example, substantial gains in greenhouse gas reduction may be achieved at the expense of biodiversity by using biofuels implicated in deforestation practices. Similarly, metered reductions in particular impacts may be undone by unmonitored activities elsewhere in the organization. For example, green building successes and GHG reductions may be completely negated by additional emissions resulting from campus growth, endowment-investment strategies, research activities, or travel emissions from study-abroad programs. Not only is a systems-thinking approach necessary for avoiding these risks, it is essential for discovering the big opportunities.

I believe that our educational institutions are ripe with prospects for significant impact reductions at no added cost. Many of these gains can be found via a life-cycle costing approach that considers long-term costs and benefits. Many more opportunities can be discovered by thinking about larger systems instead of separate components. For example, universities could switch to 100% post-consumer recycled paper at no added cost if they simultaneously adopted double-siding practices for all printers, copiers, and publications. Dining facilities could increase local, fair trade, and organic options at no added cost if students would agree to reduce the diversity of meal offerings and eliminate food waste. At Harvard, I worked with a graduate student to investigate a systems-thinking approach to reducing building-related GHG emissions. In our case-study, a 120,000 square foot residential building built in 1959, we were able to show on paper that by investing in energy efficiency, capturing those savings, and reinvesting them in other GHG-reducing activities, over a twelve-year investment period the net present value cost for achieving climate neutrality (zero net GHG emissions) for that one building would be just US$6,000 in today's dollars.

Systems thinking presents us with such a profound challenge because it forces us to confront the way in which university functions are compartmentalized into divisions, units, departments, disciplines, and tiers of management. While this approach enables a good degree of control and accountability up the chain of command, it also ensures that the whole system is rarely considered when decisions are made. Whether it is the campus-energy system, purchasing, transportation, waste, or water system, there are numerous structured disconnects between all of the relevant stakeholders, with little or no effort to transcend these separations at critical planning times. All effort is directed toward optimizing single parts of the system, even at the expense of the institution overall. At one university I worked for an entire new campus was under development, but we were still unable to get the utility planning and the building-design teams to collaborate on downsizing the associated utility plant to reflect a commitment to more energy-efficient buildings. The architects did not want to answer to the utility-planning team's requirements and the utility-planning team was preoccupied by the concern that the client would blame them, not the building designers, for any shortfall in utility provision. In one of the most ironic examples of how the culture of separation endemic to our organizations makes it so hard to make real progress, a particular green building renovation project was tested to see if it was tightly insulated enough to pass the required blower door test to become ENERGY STAR rated. It was discovered, after the fact, that the group conducting this test used a tracer gas called SF6, which happens to have a GHG potency of over 25,000 times that of carbon dioxide. It was only used in very small amounts; however its potency meant that even these small amounts were problematic.

We will not be able to realize the benefits of systems thinking until we address the separations of our universities. To think about systems effectively you need to bring the people that represent each of the system components into the room, that is, all of the key individuals who represent the system must engage in conversation before you can understand and identify system-level opportunities and implications. The nature of this conversation must advance beyond a dynamic of territorialism and component optimization toward a dynamic of deep collaboration and engaged interdisciplinary thinking. To this end, the people must be effectively incentivized and facilitated from beginning to end to strive for shared success and to generate team-based problem definition and solution development. To date, we have very few examples of effective systems thinking being achieved in our universities, but recognition of its importance is growing.

We now need to usher in the third wave of the campus sustainability movement, an era focused upon addressing the irrational and unconscious aspects of our institutions to foster a new organizational capacity for innovation and transformation, steered by a systems-thinking perspective. It must be led with authority and influence, exerted by presidents and executives, middle managers, and grassroots champions. We need leaders with a sober, realistic, and sophisticated grasp of how our institutions truly function, and a more accurate assessment of how much we can depend upon pure rationality and when we must address the less rational, unconscious, and more complex nature of our organizations. We need leaders who are willing to face the risks and opportunities that will arise by engaging in conversations that explore the very distribution of power, the architecture of decision-making processes, and the nature of governance, in pursuit of a new level of shared ownership and interconnection across all necessary disciplines, management tiers, and administrative functions. We must work to strengthen bottom-up and horizontal collaboration, continuous learning, and capacity building. We need to enable a systems-thinking approach to steer the course toward campus sustainability. Only by ushering in this next wave in the campus sustainability movement will we manage to navigate the next era of the long and complex journey to bring our institutional impacts down to an equitable share of what the planet's life-support systems can support.

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About the Author

Leith Sharp has eighteen years of experience in greening universities around the world. She has consulted and presented to over 100 organizations and is on the governing committees and editorial boards of numerous organizations, including the Association for the Advancement of Sustainability in Higher Education and the *International Journal of Sustainability in Higher Education.* Leith has received numerous awards for her work including a Churchill Fellowship and Young Australian of the Year, NSW Environment Category. From 2000 to 2008, Leith was the founding director of Harvard University's Green Campus Initiative and led the creation of the largest green campus organization in the world, taking Harvard to the forefront as a global leader in campus sustainability. Under her leadership, Harvard achieved over 50 LEED building projects (mostly gold or better), instituted a US$12 million revolving loan fund that achieved an average return on investment of 30%+, and implemented wide-scale engagement in occupant behavioral change, onsite renewable-energy projects, GHG reduction commitments, alternative fuels, green cleaning, environmental purchasing, and much more. Leith is currently engaged in a variety of writing, teaching, speaking, and consulting activities. She has an ongoing affiliation as a visiting scholar with the Harvard School of Public Health and continues to teach organizational change management for sustainability and green building design through Harvard's Extension School. Leith has a bachelor's degree in engineering (environmental) from the University of New South Wales (Australia) and a master's degree in education (human development and psychology) from Harvard University. She welcomes feedback and can be contacted via lsharp@hsph.harvard.edu or leithsharp@yahoo.co.uk.

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ARTICLE

Large footprints in a small world: toward a macroeconomics of scale

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The question of scale has been of ongoing interest in the sustainable development discourse, particularly with regard to the size, geographical extent, and complexity of human systems. However, this consideration has not sufficiently informed the practical implementation of sustainable technologies and there remain echoes of historical debates over “small is beautiful” versus “bigger is better” that dominated environmentalism during the 1970s. The complex adaptive nature of social and ecological systems suggests that trying artificially to choose a scale for systems is the wrong approach. A properly managed system should self-organize to a scale that optimizes economic prosperity while respecting ecological limits. For this outcome to occur, however, we argue along the lines of Herman Daly for the effective use of macroeconomic tools. Though the specific form of these tools remains undefined, we draw on complex systems theory to suggest four possible properties based on the concepts of resilience and transformability. These properties are then applied to the food system to demonstrate the self-organization of scale.

KEYWORDS: environmental economics, food consumption, systems analysis, population-environment relationships, ecosystems

Introduction

As human societies continue to grow and expand their resource requirements and waste-sink needs, their impact upon supporting ecosystems is transitioning from negligible and easily accommodated to a level of disturbance that could, and often does, exceed the resilience of the ecosystems involved. This shifting balance is at the root of our environmental challenges and is fundamentally a question of scale. Where once human societies were small enough that they could not disturb the highly resilient ecosystems of the biosphere, human-waste streams and resource needs have now grown to a scale where they can have very broad and long-ranging impacts.

Scale is a critical consideration for sustainable development. As Jordin & Forton (2002) note, “Inseparably alloyed to the scale issue are topological relationships in ecological systems, which require respect for, and maintenance of, their integrity and services. Thus, sustainability is a scale and topology issue–in other words, sustainability must respect the shape and form of the landscape and its prominent features. Despite this critical link, research into scale in the social sciences has been imprecise (Gibson et al. 2000), perhaps due to the historical separation of science and social science in most research institutions. In the environmental context, this question of the “proper” size and scale of human enterprise has largely been framed in terms of the limits to the biosphere’s ability to support human society, for example as argued in the *Limits to Growth* report (Meadows et al. 1972). Scale is intuitively integral to sustainable development. Working within a system with fixed limits implies an optimal scale for human systems that is not too small to take advantage of economies of scale, but is not so large as to overwhelm ecological support systems. To ignore such considerations means that the economic system grows unnaturally outside of its productive capacity. Ecological and social systems are multifaceted and exhibit properties of complex adaptive systems such as path dependence, emergent behavior, unpredictability, and unexpected feedback loops (see Newman, 2005 for a more detailed exploration). It is unlikely that an optimal scale could be chosen or anticipated in advance. Sustainable development is a dynamic process and the common approach within the literature of suggesting a “correct” scale is not compatible with the unpredictable nature of complex system dynamics.

This article explores how the concept of scale has evolved within environmental debates, with a focus on Herman Daly’s call to develop and use macroeconomic instruments. We look to complex systems theory to suggest some of the properties that these instruments might reflect and conclude by discussing a complex human-ecological system—the food system—in the context of these characteristics. We contend there is a need for better understanding

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of the factors that contribute to the scale of social systems.

The Concept of Scale

The concept of scale is complicated and variously interpreted by different disciplines. For instance, in ecology one use of the term refers to the relationship between the extent of an activity and the size of its containing environment. In landscape ecology, it is often stated that "scale matters," and certain activities are described as "scale-divergent" meaning that their impact is different depending on the scale at which they are occurring (Schneider, 2001). Political scientists frame scale as an outcome of physical constraints, politics, technology choice, institutional structure, and available information (Lebel et al. 2005). In microeconomics, scale is most often discussed in terms of economies of scale—benefits that are realized by expanding production that, in the case of individual companies, are eventually balanced by diseconomies of scale, and suggest the existence of an optimum size for each organization (Daly, 1992). However, the field of macroeconomics has no real parallel idea, no suggestion that the economy as a whole, or certain subsectors of it, have optimum sizes. Ecological economists such as Herman Daly (1992) vigorously contest this omission, arguing that macroeconomic scale has not been formally recognized and has no corresponding policy instrument. Among geographers, the concept of scale can be confusing, as it has several meanings. The one use germane to the current discussion is phenomenon scale, which refers to the size at which human or physical earth structures or processes exist, regardless of how they are studied or represented (Mason, 2001).

Daly (1991) brought the issue of scale in association with the nature-culture interface to prominence by highlighting the neglected connection between macroeconomics and the environment. He defined environmental macroeconomics as being concerned with flows between the economy and the environment and noted that microeconomics is akin to loading cargo onto a boat and that there is an absolute limit to how much any one boat will carry regardless of how the cargo is arranged. Daly pithily asserted, "Optimally loaded boats will still sink under too much weight even though they may sink optimally." He went on to further claim that this problem needs to be solved using a "non-existent policy instrument." Unfortunately, after the passage of 18 years, no such instrument has emerged into common use, though some interesting possibilities, such as ecological footprinting, have been applied in limited situations at various scales (see, e.g., Wackernagel & Rees, 1994).

The lack of a policy instrument is not an indication that the problem is not severe, but rather highlights the difficulty of addressing complex dynamics. Cumming et al. (2006) discuss the issue of scale mismatches and claim that

> When the scale of environmental variation and the scale of the social organization responsible for management are aligned in such a way that one or more functions of the social-ecological system are disrupted, inefficiencies occur, and/or important components of the system are lost.

An explicit study of scale has not been forthcoming. The issue of scale is also confounded by customary natural resource-management policies that discount cross-level, scale-dependent interactions in favor of the pursuit of maximum yields, a practice that has led to spectacular resource collapses (Young, 2006). Many scale issues evolve over decades, plus most measurements are local and patterns measured locally do not necessarily hold at large scales (Schneider, 2001). The focus on "small is beautiful" among environmental critics has led to the framing of these failures in terms of taking "too much, too fast" from ecosystems, which is certainly a factor, but this framing does not capture the many subtle effects at work. The critical question is: How does scale-dependent interplay affect the sustainability of key biophysical systems, especially those systems that are dominated by human actions? A sustainable scale requires applied knowledge of the spatial-temporal constraints of ecological systems and linkages, knowledge that is still imprecise (Jordan & Fortin, 2002).

Outside of the subgenre of adaptive management, the concept of scale in traditional environmental discourses has lacked the robustness needed to reflect the real qualities of complex adaptive systems. The dominant paradigm that has informed these debates for many years asserts that the scale of interaction should be small wherever possible, though this attitude has diminished in environmental circles, particularly in the era since the 1987 Brundtland Commission. This is not to say that the idea of small-scale endeavors as routes to sustainable development was not revolutionary in its time. Schumacher (1973) argues in his famous book *Small is Beautiful* that we should limit the size of human enterprise relative to nature to reduce the chance of serious harm and this position has been very influential in certain environmental discourses. Some writers like Duane Elgin (1981) particularly target the complexity of our social systems as a problem and others, such as Ted Trainer (1998), take this position to its extreme by calling for self-sufficiency, smallness, decentralization, and extreme simplification. Even those authors who make an honest effort to explore the benefits of small scales are prone to falling into the trap of wishing for a simple society. For example, Papworth (1995) begins his book, evocatively titled *Small is Powerful*, with a reasoned explanation of the benefits of local resource management, but quickly digresses into an argument for the end of cities and markets and a return to a rural, agrarian lifestyle. According to scholars like Morris (1996), "Small is the scale of efficient, dynamic, democratic, and environmentally benign societies," but this emphasis on smallness can also be motivated by wishful thinking for a nostalgic past. More recently, some "peak oil" theorists have recommended a return to small-scale society as a response to the decline in fossil-fuel availability (see, e.g., Kunstler, 2005). At the same time, a dissenting school of thought advocates in favor of large-scale expansion of energy distribution systems (see Newman, 2007). Such continuing polarization leads to the "law of the excluded middle" and marginalizes solutions that transcend dichotomy.

Why has conventional environmentalism focused so intently on the small? It is perhaps a natural human response upon encountering a complex adaptive system to seek simplification to remove complexity and risk. In the past, a single preagricultural human required the Earth to supply a bit under 2,600 kilocalories (kcal) of energy a day, about the same as what a common dolphin requires. In contrast, a single *Homo colossus* [Catton's (1980) term for a contemporary industrial human in the United States] requires the equivalent of a sperm whale's daily supply of more than 202,700 kcal. In times of low population and per capita-resource use, the debate over "small is beautiful" versus "bigger is better" would have been largely an unimportant one as the biosphere dwarfed humanity's impact upon it. This response today, however, is, at best, wishful thinking and, at worst, destructive. Tompkins & Adger (2004) note that adaptation is not about returning to a prior state. Moreover given that we now live in a complex, coevolving socioecological system (Norgaard, 1994), the notion that we could successfully wall off our communities and activities into isolated local enterprises is unlikely, especially given global economic interdependencies with accelerating tendencies to large scale. As Berkes (2006) observes, small-scale systems are rarely free of external drivers, and it is only by accepting the need to engage on many scales that we can successfully respond to challenges in ways critically linked to community resilience.

The other side of the discourse is equally one-dimensional. Critique of the "small is beautiful" concept reached its zenith with the works of the economist Julian Simon (1996). Calling human intelligence the "ultimate resource," he argued that resource replacement and substitution is so easy for us that we will never run out of anything. In the ultimate expression of bigger is better, Simon envisioned exploiting the solar system, and perhaps the galaxy, in an expansion that has no real barriers for hundreds of millions of years. Beckerman (1995) expressed similar, if slightly more nuanced, views in his book, *Small is Stupid*, and suggested that human ingenuity can always work around resource scarcity, but only if we allow economic processes to be as large as possible. Beckerman also relied heavily on the environmental Kuznets curve (EKC), a theory suggesting that as societies develop economically their environmental impact first grows and then falls again after passing a certain per capita-income threshold (see also Grossman & Krueger, 1991). Bigger in this context is not only better, but cleaner. It should be recognized, however, that the EKC does not seem to hold true in many cases, particularly with regard to resource management. Currently, writers such as Lomborg (2001) present the same arguments for "bigger as better" in more polished form. Given the failure of multiple managed resources, particularly with respect to marine resources, it is curious that communities and governments have not more vigorously challenged "bigger is better" policies. However, many elements of society are heavily invested in conventional natural resource use. The popularity of technological fixes, such as carbon capture and storage to control carbon emissions, reflects the belief that, with technological innovation, we can grow our way out of any problem.

There are serious flaws with the neoliberal view charging that Daly's limits are specious given human ingenuity and capacity for technological innovation. At least until the current economic downturn, markets were seen as self-correcting and the main solution of the neoliberal theorist was "less government intervention." However, as Ayres (2007) observes, there is a limit to substitution. For example, light-emitting diodes (LED) convert a very high percentage of energy input into light, so improvement beyond refinement is unlikely. Some things cannot be replaced: "The biosphere embodies a fundamental natural technology for which there is no known alternative and which is truly essential to human survival" (Ayres, 2007). Inventiveness also has limits and there is no guarantee that we can innovate rapidly enough in a world where human systems approach the scale of the natural systems in which they are embedded (Bretschger, 2005; Newman et al. 2008). If exponential growth were to continue, we would need a corresponding exponential rise in innovation.

Though bigger might not be better, throughout history this strategy has proven very effective at reducing the diversity of smaller enterprises. Oram & Doane (2007) aptly note, "The small rarely survives in a world where narrowly defined measures of economic efficiency are the only determinants of success." Moreover, institutional rigidities and incentives that support the large at the expense of the small worsen the problem. In many of the case-study communities we have investigated, local enterprise is largely extinct. The mismanagement of scale-dependent environmental resource regimes demonstrates that a focus exclusively on one scale at the expense of allowing maximal, rather than optimal, scales to emerge obliterates opportunities for critical feedback and information (Young, 2006). If bigger is not better, and small is not beautiful, what is the optimum scale for social-ecological interactions?

Asking a Different Question

We must address the nature of the needed policy instruments to improve our understanding of the dilemma of scale. This article suggests four aspects of complex adaptive systems that theorists and practitioners should consider in any policy instrument designed to reconcile the scale of societal impacts and the scale of the biosphere. There are likely other important aspects, and, in a few cases, not all four will be relevant. However, our experience with the practical application of various sustainable development technologies and action plans has been that these aspects reappear in almost all cases (see, e.g., Dale et al. 2009).

The nested and interconnected set of scales operating within a system of social-ecological interaction should ideally optimize two qualities critical to sustainable development: resilience and transformability. Holling & Gunderson (2002) define resilience as the magnitude of disturbance that can be absorbed before a structural change occurs. While a system should be able to maintain a degree of stability in the face of surrounding change, sometimes system change is required for long-term sustainability. This capability is known as transformability, the ability to totally alter subsystems if needed (Walker et al. 2004). We also note that, as with many properties of complex adaptive systems, these classifications are necessarily "blurry" and there is certainly some degree of crossover.

The four conditions are as follows:

1. All required independent variables must be considered or integrated into decision making.
2. Communities must employ adaptive comanagement at all subscales to allow local feedback to work its way up through the system.
3. A diversity of options must be available.
4. Processes to prevent lock-in must be in place.

Considering All Required Variables

For any system to be optimally scaled within a surrounding environment, multiple variables must be considered. In short, "how we think about scale depends on what we think is important" (Norgaard, 1994). This observation is abundantly clear with respect to resource management. If, as is often the case, only short-term economic interests are considered, overexploitation of the resource quickly follows. Within the "bigger is better" world of neoliberal economics, the relegation of certain variables, such as harmful emissions, to the category of "externalities" that are not considered in economic calculations removes crucial feedback and allows the scale of our activities to become too large. Sustainable development cannot rely on the notion of optimal solutions based upon a single measurement (Rammel & Van Den Bergh, 2003). The traditional emphasis on maximum yields in natural resource-management policies has led to astounding ecological collapses in fisheries and forests. Kai Lee (1993) attributes this problem of overexploitation to a mismatch of scales and notes that, "When human responsibility does not match the spatial, temporal, or functional scale of natural phenomena, unsustainable use of resources is likely, and it will persist until the mismatch of scales is cured."

If evaluating all variables related to economic, ecological, and social sustainability would lead to optimal scale, why are so many social-environmental interactions evaluated on only a few variables, or often only on variables associated with economic growth alone? Traditional planning has involved isolating variables of interest, but this approach has decreased resilience (Gunderson, 2000). Though a lack of understanding of environmental impacts and simple expediency both play roles, the delayed nature of our impacts on environmental systems also causes problems. It often requires the passage of years before we come to understand the impacts of our actions. Unfortunately, economists have trouble with slow-moving variables and delayed feedback and tend to focus on fixing issues in the short term (Holling et al. 2002). Diamond (2005) calls this the problem of creeping normalcy—unless we are paying close attention to ecosystems, we can fail to notice system changes that occur over long periods. It is likely that we not only have to observe all relevant social, ecological, and economic variables, but we must do so over a long enough time.

Within the consideration of all variables, there is a normative aspect regarding what goals a society considers at a particular time and who considers them. By favoring some variables over others, we can distinguish between the maximum sustainable scale and the optimal sustainable scale (Lawn, 2001). The optimum scale respects variables necessary for allowing us to meet our social desires, reconciling those with ecological and economic imperatives (Dale, 2001). The amount of free time deemed necessary, for example, might delineate a difference between the optimal and maximal scales.

Implementing Adaptive Comanagement

If we are to respect all relevant variables within a system, we must create institutions that are open and capable of responding to environmental feedback. One of the problems with our customary views of scale is that within complex adaptive systems we do not decouple activities occurring on different scales. A system is not simply large or small, but rather contains nested scales from the overall largest down to local subscales. This structure is central to the resilience of complex adaptive systems, *provided the various scales talk to each other*. Social systems and ecosystems require flexible governance and the ability to respond to environmental feedback (Olsson et al. 2004), and often the feedback arrives at a different scale than the one at which action must be taken. Comanagement across scales is thus critical to solving complex problems (Cash et al. 2006). Some scholars have identified the problem of "fit" between institutions and scale of analysis as a condition for sustainable development that requires working at multiple scales and cross-scale analysis (see, e.g., Folke et al. 2007). As Kastenhofer & Rammel (2005) note, sustainable development is a process of compromise requiring a balance between long-term efficiency and resilience.

Adaptive comanagement of ecosystems that considers both local actors and larger level effects is critical to the creation of resilience and transformability. Use of local ecological knowledge builds resilience as local solutions become tailored to local conditions in ways necessary for healthy ecosystem interactions (Berkes et al. 2000). If many variables are monitored, changes will first be observed "on the ground" locally. Without local involvement, management tends to shift towards exploitation. As local resources are depleted, new resources are substituted in other locations. Focus on a single scale tends to emphasize processes at that scale and to oversimplify the system, sometimes ignoring critical variables (Willbank & Kates, 1999). Gunderson & Holling (2002) capture the complexity of our systems across scales with their term "panarchy," which refers to a set of dynamic systems nested across scales. While governments have yet to usefully define and implement this concept, only by addressing all levels within the panarchy can we get a full understanding of the system and its limits.

The need for local knowledge and observation is not, however, an argument in favor of moving to locally isolated small-scale enterprises. As even local action can have global consequences, resilience emerges from both cross-scale and within-scale interactions (Peterson, 2000). Transformability in the face of external changes requires an outward focus to the larger scale. Connectivity allows resilience and movement, but the existence of local network structure buffers against cascades of disaster from the larger world (Andersson, 2006). That said, for adaptive comanagement to work effectively, it must be collaborative, as without a shared sense of purpose stakeholders at different scales are likely to have very distinct interests. In most cases, global stakeholders are likely to value short-term financial gain over local ecosystem integrity, but, in other cases, local actors might value short-term employment prospects over larger ecological needs. Actors at all scales must work in concert, not at cross purposes.

Creating a Diversity of Options

Ecosystems are divergent under small changes in environmental variables. In other words, if the same species colonizes two slightly different ecological niches, it will then adapt differently in the two places. This is a common resilience-building strategy within complex adaptive systems, making the standardization desired by global economic interests quite puzzling. Ritzer (1996) notes the huge inefficiencies involved in standardization and describes how the savings are often short-term and local. He gives the example of "just-in-time" manufacturing, which saves individual companies money, but clogs the roads with nearly empty trucks.

With diversity comes strength through the preservation of options. Rammel (2003) notes that the preservation of diverse approaches within an economy does not always generate optimal short-term returns, but such a strategy does provide long-term flexibility. Other authors have additionally noticed the lack of diversity in our economy. For instance, Araujo & Harrison (2002) argue that to preserve our agency to act, it is best to hedge bets and maintaining diversity can serve as a useful way to minimize risk (see also Rammel & Van Den Bergh, 2003). Diversity is fundamentally connected to local resilience in a community's ability to respond and adapt in an appropriate time to exogenous variables. In addition, innovation requires accurate price signals and research-friendly environments (Bretschger, 2005).

Intellectual and technical advances will only occur in a robust culture of research, which builds resilience by creating an array of options.

Diversity can be preserved within social-environmental interactions through the encouragement of niche exploitation and "niche accumulation": the adoption of new technologies within specific sets of environments or circumstances in which they enjoy an advantage, allowing them to spread to similar niches. Technical niches protect new technologies from premature rejection (Raven, 2007). Whether experimental niches are available within a society depends on the attitude of the relevant power brokers. Government can encourage niche exploitation or can use regulation to make niche exploitation all but impossible (Rammel, 2003). "Testing" a technology or procedure in a few small niches can help overcome obstacles and, as Raven (2007) points out, this process can lead to "niche branching" in which the technology spreads to a larger, less specialized niche. Kemp et al. (1998) see this as central to the quest for sustainable processes and argue that sustainable technologies will look slightly different in each specific place of application.

Each local context provides a variety of niches for innovation and experimentation. Such spaces are compared to ecological "edge spaces" and function as zones for social interaction, cross-fertilization, and synergy as they increase resilience and are purposely created in some communities. Examples vary from the creation of public space, such as the new city square in Rockville, Maryland, to special zoning to encourage innovation, such as the conversion of manufacturing districts into a public market and space for artists on Granville Island in Vancouver, British Columbia (Rockville, 2007; Granville Island, 2009).

Niche space can also be created by circumstance. Unruh (2002) demonstrates how niche exploitation can encourage a new technology using the example of Edison's electrification of the lighting on the steamship SS Columbia in 1880. Because gas and oil lighting were very dangerous aboard ship, there was an increased openness to experimentation. Such niches can act as a demonstration case for new ideas and technologies. The standardization found in the large-scale corporate model can constrain niche availability, reducing diversity and limiting niche technologies. At best, we passively exploit diversity within our societies to test new processes and technologies (see, e.g., Newman et al. 2008).

Preventing and Correcting Lock-in

If all system variables are under consideration and a signal propagates through a system suggesting a change is needed, it is not assured that the needed change will be possible. Technologies, ideas, and behavior patterns can become entrenched and intertwined, creating a problem known in the literature as "lock-in." Scheffer & Westley (2007) describe lock-in as "ubiquitous" despite the fact that it prevents adjustment to new situations. Diamond (2005) calls this reluctance to abandon what we have even if it does not work the "sunk cost effect" and attributes it to the fact that we have already invested time, energy, and resources in an inferior alternative. Lock-in arises naturally out of two properties of complex systems: path dependence and increasing returns. Technologies and procedures coevolve and so certain system elements take up the role that keystone species play in ecosystems. One cannot simply change them without setting off cascading changes throughout the system.

Path dependence can be described as "reactive sequences" in which each event is precipitated by previous self-reinforcing sequences (Mahoney, 2000). In short, history matters, and a random event can ensure that a suboptimal technology or process becomes the norm. Rammel (2003) points out that sometimes rather mediocre solutions dominate a natural selection process in the short term and that systems—particularly ones of great complexity—can prove very inflexible. Arthur (1994) calls this reenforcement of certain historical paths nonergodic behavior and path dependence matters deeply in his analysis. Although this problem could be minimized by careful use of precautionary principles at the beginning of the development of a technological path, negatives of new technologies often appear after implementation and policies frequently have unintended consequences. The use of chlorofluorocarbons are an example of the significant lock-in of a technology occurring prior to a substantive danger becoming apparent. Identifying a problem and choosing a solution are difficult, but often, as Homer-Dixon (2000) notes, implementation of a solution is the true dilema. Lock-in is a huge problem caused by the increasing returns to mass adoption inherent in many technologies (Carrillo-Hermosilla, 2006).

Recognition of this problem is not new. In his work on the need to shift away from fossil fuels, Unruh (2000) calls lock-in a technological "cul de sac," at its worst cumulating in an embedded technoinstitutional complex that entails the interdependence of a great number of practices and technologies. Society must tackle path dependence and lock-in, but as Unruh (2002) notes "the question of how to overcome large scale lock-ins has been little explored." Unruh (2002) has related lock-in to a lack of diversity (discussed above as condition three) and the encouragement of niche markets is a possible way of breaking lock-in. However, research has shown that in extremely locked-in systems, investigation of options falls to near zero, probably reducing innovation (Redding, 2002). As Arthur (1994) notes, there is a minimum cost for a transition and changing by fiat is sometimes necessary. Correcting lock-in is a critical component of adaptive comanagement, but few successful examples of this process are available.

Scale and the Food System

To illustrate how the four aspects of complex adaptive systems discussed above play out in a real system, we examine how each manifests itself with respect to the production and consumption of food. The transfer of food from ecosystem to table is one of the largest and most important social-environmental interactions. As food production can occur on scales from the microlevel of a backyard-garden plot, to the macrolevel where a single monoculture farm can spread to the horizon, to international institutions that facilitate global exchange, the food system provides an example of how the four conditions influence the self-organization of scale. The food system has overwhelmingly moved to the largest possible scale with the advent of "monster" farms fed by petroleum and supply chains that span the globe. However, a robust countermovement for organic and local food also exists, highlighting the tension between bigger is better and small is beautiful. The four variables are discussed in turn below.

Considering All Required Variables

Food chains are a revealing example of systems where diverse considerations come into effect, as optimal food systems involve many variables. Currently, the primary variables considered by producers and distributors are cost of food and stability of the food supply, but other variables of interest include ecosystem health, food safety, human-health benefits, security of the overall system, social justice for workers, and, of course, taste. Furthermore, climate change has augmented concern for embedded transportation costs. The current industrial food system has relied on plentiful fossil fuels and huge government subsidies to provide what is arguably the cheapest food in history, and one could argue that the food supply has never been so reliable, in the short term at least, for so many people. Given this reality, it is not surprising that local-scale food production has been all but obliterated in many parts of the world. Perhaps the surprise is that an alternative food system comprising local production and a growing network of organic producers that addresses food's forgotten variables has managed to survive at all. That large-scale industrial agriculture damages the environment is hard to argue. Eldredge (1998) calls loss of topsoil one of the most serious hazards facing humanity and Shiva (2000) sees soil loss as a threat to cultures and communities around the world. Some consumers are willing to pay a premium for organic food, in part because organic growers agree to protect their farmland (Delind, 2006). Organic and local foods are also seen as safer, a perception driven by food scares within the industrial system (Vindigni et al. 2002). Ongoing breakdowns in the security of the food system, such as bovine spongiform encephalopathy (BSE) and E. coli outbreaks, have fueled this perception. Local production is also thought to produce fresher and tastier food (as varieties do not have to be chosen for durability over long distances), and regional development and local economic benefit (as local farm economies are preserved) (Nichol, 2003). Delind (2006) echoes these advantages, arguing local food boosts proximate rural economies, is healthier and better tasting, reduces energy needs, and fosters a sense of place. Growers and market organizers often highlight flavor and variety, and proponents often link the preservation of biodiversity with the consumption of local cultivars, which has also emerged as a strong social-justice issue (e.g., Shiva, 2000). A food system that considers all of these variables will, in the long run, be more resilient than an industrial system based on soil exploitation and the existence of cheap fossil fuels.

Adaptive Comanagement Is In Use

Though the industrial food chain deploys little in the way of adaptive comanagement, several sub-streams within alternative agriculture follow the basic tenets of adaptive comanagement. One such concept is permaculture as developed by Mollison & Holmgren (1978). Initially focused on "permanent agriculture" that needs no outside fertilizers and is self-seeding, the concept has expanded to embrace the creation of sustainable human-living spaces in which edible ecosystems are designed to resemble their wild counterparts. Permaculture is about recognizing webs, such as the interaction between the sun, plants, pollinators, fungi, and other elements of an ecological system.

Local food markets also serve an overlooked educational and social purpose introducing new foods into people's diets and highlighting cooking methods, which is especially important given the importance of scale to food quality and nutrient density. Surveys in the Niagara rural region of Ontario, Canada found that farmers' market customers enjoy the chance to interact socially with others interested in local food and with the producers themselves (Feagan et al. 2004). Local foods lack many of the hidden costs of industrial agriculture and shorten the distance between grower and consumer. In contrast, a largely globalized food system has embedded transportation costs and the nutrient value of food sources decreases when transported over long distances.

A Diversity of Options Is Encouraged

Industrial agriculture discourages diversity, increasingly putting all of our metaphorical (and literal) eggs in one genetic basket. This focus on uniformity has led to the widespread destruction of landraces, the variations of major crops adapted to local environments grown by small-scale farmers. As an example, of the 7,000 apple varieties once grown in the United States, 6,000 are now extinct (Shiva, 2000), a phenomenon matched by the destruction of wild relatives to major crops (Douthwaite, 1996). Losing these pools of genetic diversity exposes us to the threat of massive losses due to disease or environmental changes. For instance, if thousands of wild varieties of potato had not been growing in South America at the time of the Irish potato famine, potatoes would likely not be a viable crop today (Douthwaite, 1996). The loss of landrace diversity has exceeded fifty percent for some key crops (see, e.g., Huynen et al. 2004). Large-scale agriculture focuses on output, not diversity. Shiva (2004) highlights the impact of this loss on local farmers who are forced to turn to high-yield varieties and must then buy pesticides and fertilizers to produce the exotic imports that local varieties simply did not need. Across the developing world, this cycle is having the same effect that it did in the developed world, notably the rapid disappearance of the local farmer.

The news, however, is not all bad. For example, the Italian gastronomic activist Carlo Petrini founded in 1989 what has come to be known as the Slow Food movement with the preservation of biodiversity as one of its key goals (Pietrykowski, 2004). Advocates argue for the conservation of local varieties and flavors that contribute to a "rhetoric of terroir" (Miele & Murdoch, 2002). The best nonliteral English transition of terroir might be "distinctness of place," the quality of a locale that makes it unique. The Slow Food movement seeks to position food as a key constituent in the development and maintenance of community (Pietrykowski, 2004). Others argue for a broader locality theme, claiming that complete neighborhoods are those that meet daily needs locally (Leyden, 2003). Though initially a European trend, local food has become popular in North America as well, particularly after the publication of the "100 Mile Diet" that strongly encourages local production as a way of achieving environmental and health benefits and as a building block of sustainable communities (Smith & MacKinnon, 2007).

Lock-In Is Prevented and Corrected

For the small niches occupied by local and organic food to expand, an overwhelming lock-in of the industrial food system must be overcome. The prospects are not entirely promising. The ability to change our food system is highly limited by lock-in with respect to our social infrastructure (Seyfang, 2007), but more importantly by market infrastructure favoring the large scale. This infrastructure includes massive subsidies for large producers, regulations that inhibit local production and processing of food, and the ever-present effect of cheap and abundant fossil fuel that allows the industrial production and distribution system to function. In the face of this challenge, alternative food systems are thriving in many small niches, in part due to education around the risks created by the industrial system. Knowledge of food production is still limited (Dillon et al. 2005), but these niches will likely continue to grow as more people become interested in their food and as fuel prices rise. Such circumstances make it possible to overcome the problems of lock-in.

The Future of Food

To summarize, the industrial food system demonstrates very clearly the results of failing to take into account the four system requirements of resilience and transformability outlined in this article. However, niche-food systems are developing that focus on local and organic food, and these alternatives are at least beginning to address the four requirements. As expected, the emerging alternative food systems are neither monolithically large nor uniformly small. The exchange of information between regions is a key component of the Slow Food movement as it is meant to be a global transformation, not a scattering of isolated projects. In addition, local food can benefit from embracing some of the economies of scale found in the industrial food system. For instance, studies show that if food production occurs at an overly small scale, energy needs can exceed those of industrial agriculture (Wallgren, 2006; Van Hauwermeiren et al. 2007) as individual farmers drive very small crops to market in fuel inefficient vehicles. This obstacle can be overcome by embedding small producers within a slightly larger distribution system. The role of supply-chain length is also variable. Certain foods that are too delicate to transport, such as specific mushrooms, are produced locally even by large corporations or they are excluded from industrial agriculture entirely. On the other hand, Van Hauwermeiren et al. (2007) found that in many cases growing local crops in greenhouses during winter months was less energy efficient than importing the same crop.

A very interesting example that highlights the nuances of the issue is a study by Sundkvist at al. (2001) that analyzes the potential for local bread production on the island of Gotland in Sweden. They found that on a per kilogram basis the bread produced locally is currently more energy intensive, though it was less greenhouse-gas intensive given the existence of shorter supply chains. However, the authors noted that this energy intensity was a result of external factors such as the unavailability of local flour and the inefficiency of the equipment used on the island. They note that

> The region has a large potential to produce enough flour for its local population and thus to become less dependent on imports. However, using more locally produced bread grain to produce flour in local mills, improving energy efficiency in small-scale mills and bakeries, changing consumer behavior and internalizing environmental costs of transportation are crucial measures in achieving this goal.

Sundvist et al. (2001) also suggest that if local sources of renewable energy were available it would offset the higher energy needs of medium-sized bakery facilities, and they observe that local flour is more nutrient rich and less environmentally harmful than industrial flours. In short, bread produced at the large scale is not the same as bread produced at the small scale, even though the market often treats the two products as equivalent. It is apparent that further studies are needed to develop a more complete analysis of the optimal extent of local production.

Conclusion

We argue that the scale of any particular social-ecological interaction is a complex quality that should evolve as an emergent property of the system's feedbacks and expectations. We agree with Herman Daly that a macroeconomic policy instrument (or suite of instruments) is needed to guide the relationship between social and ecological scales and we suggest that such an instrument must be grounded in complex adaptive systems theory, as both social systems and the biosphere are dynamically interconnected, complex, and adaptive. We suggest four qualities of such systems that we contend could provide a basis for policy-relevant instruments: that all needed variables must be considered, adaptive co-management must be present to incorporate feedback at different scales, a diversity of responses must be available, and lock-in must be corrected and avoided. Although these four aspects are not universal and are not exclusive, they are crucial. One could consider the first two aspects as requirements of resilience and the second two aspects as requirements of transformability. Moving forward, it is critical that we improve our understanding of the requirements of transformability, particularly the ability to correct and prevent the economic, social, and institutional lock-in that emerges within path-dependent processes.

The complex nature of social and ecological systems does pose a challenge to understanding the four aspects. Certainly identifying all of the variables within a system with sensitive dependence on initial conditions and emergent behavior is difficult. Likewise, a precautionary approach within a complex system will be at best only partially successful. These obstacles can be mitigated by using a series of iterative evaluation processes. For example, important variables may become apparent over longer periods. Controlling technological and social lock-in might best be achieved by innovative public policy to support niche markets through government subsidies. It is much easier to shift to another path when the alternative does not have to be invented from scratch. Unfortunately, the current subsidies that most countries provide to incumbent systems enforce rather than challenge homogenous markets. In addition, the funding of research and innovation of all types could improve the diversity of options available.

The above consideration of scale is more than an academic exercise. The tendency to ignore the four factors discussed above, coupled with our high population and per capita-resource requirements, has led to the proliferation of activities totally out of proportion to the resource bases upon which they rely. It is critical that we address this mismatch if we are to repair the integrity of impaired social and ecological systems.

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ARTICLE

An evaluation of criteria for selecting vehicles fueled with diesel or compressed natural gas

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We reviewed selection criteria for diesel and compressed natural gas (CNG) fueled vehicles, comparing engine emissions, fire and safety, toxicity, economics, and operations. Diesel- and CNG-fueled vehicles with the latest emission-control technology, including engine-exhaust aftertreatment, have very similar emissions of regulated and unregulated compounds, particles through all size ranges, and greenhouse gases. Although toxicity data are limited, no significant toxicity differences of engine emissions were reported. Operating and maintenance costs are variable, with no consistent difference between diesel- and CNG-fueled vehicles. The main operating concern with CNG vehicles is that they are less fuel efficient. Higher infrastructure costs are involved with implementing a CNG-fueled vehicle fleet, giving diesel vehicles a distinct cost advantage over CNG vehicles. For a given budget, greater emissions reductions can thus be achieved with diesel+filter vehicles. Finally, diesel vehicles have a significant fire-and-safety advantage over CNG vehicles. In summary, infrastructure costs and fire-and-safety concerns are much greater for CNG-fueled vehicles. These considerations should be part of the decision-making process when selecting a fuel for a transportation system.

KEYWORDS: fuels, engines, automotive exhaust emissions, safety, greenhouse gases, cost-benefit analysis

Introduction

To improve air quality, many regions in the United States are considering alternative fuels such as compressed natural gas (CNG) to replace diesel. For example, California's South Coast Air Quality Management District (SCAQMD), with a jurisdiction over an area that covers the counties of Los Angeles, Orange, Riverside, and San Bernardino, enacted rules several years ago encouraging government fleets to purchase natural gas vehicles (e.g., SCAQMD, 2001). In contrast to SCAQMD, other regions, such as the Massachusetts Bay Transit Authority (MBTA), have considered CNG to replace diesel to improve air quality, but decided to continue with diesel-fueled transit buses (Heywood et al. 2002). The opposite decisions of SCAQMD and MBTA may reflect different political forces and public perceptions in the respective outcomes (Hess, 2007; Valderrama & Beltran, 2007). Past decisions thus do not provide an objective path for fuel selection. To make the most beneficial fuel choice, several other criteria should ideally be considered, including, but not limited to, fire and safety, toxicity, economics, and operations. To aid decision makers in selecting a fuel for their transportation systems, this review summarizes the data available on these criteria and identifies substantiated similarities and differences between diesel- and CNG-fueled vehicles.

Emissions

Regulated and Nonregulated Compounds

Government officials frequently cite emissions benefits for the selection of CNG-fueled vehicles over their diesel alternatives. For example, SCAQMD favors CNG because, according to their research, diesel emissions account for 71-84% of the increase in cancer risk from toxic air pollutants (SCAQMD, 2000; 2008). In contrast, other studies of transit buses show that regulated and nonregulated emissions can be elevated with either diesel or CNG-fueled vehicles when there is no exhaust aftertreatment (Hesterberg et al. 2008). To meet emission standards set by the United States Environmental Protection Agency (EPA), new diesel- and CNG-fueled vehicles have exhaust emission-aftertreatment devices. The diesel-aftertreatment device is a catalyzed particulate filter (diesel+filter) that reduces particulate emissions. Similarly, the CNG-aftertreatment device is a catalyzed muffler (CNG+catalyst) that reduces total hydrocarbon emissions. These devices provide additional benefits by lowering the emissions of unregulated compounds

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Table 1 Regulated and related emissions and fuel economy in transit buses (in grams/mile).

Compound	Diesel	Diesel+Trap	CNG	CNG+Three-Way Catalyst
Carbon Monoxide	7.71 ± 1.91[a] 21[b] [2,3][c]	0.62 ± 1.66 28 [1,3]	14.16 ± 1.63 29 [1,2,4]	4.93 ± 2.34 14 [3]
Total Hydro-carbons	1.11 ± 1.93 21 [3]	0.10 ± 1.84 23 [3]	18.95 ± 1.67 28 [1,2,4]	3.45 ± 2.36 14 [3]
Particulate Matter	0.63 ± 0.04 18 [2-4]	0.03 ± 0.04 28 [1]	0.05 ± 0.04 25 [1]	0.04 ± 0.06 11 [1]
Nitrogen Oxides	27.7 ± 3.1 24 [4]	26.2 ± 2.9 27 [4]	26.6 ± 2.8 29 [4]	7.7 ± 4.0 14 [1-3]
Nitrogen Dioxide	1.68 ± 2.13 6 [2]	11.61 ± 1.35 15 [1,2,4]	4.12 ± 1.74 9 [2]	0.10 ± 3.69 2 [2]
Carbon Dioxide	2384 ± 286 17	2836 ± 231 26	2703 ± 231 26	2291 ± 372 10
Nonmethane Hydrocarbons	0.85 ± 0.65 2	0.03 ± 0.32 8 [3]	1.64 ± 0.25 13 [2,4]	0.29 ± 0.46 4 [3]
Methane	0.03 ± 12.63 2	0.00 ± 6.31 8	9.97 ± 10.30 3	2.75 ± 8.92 4
Miles per Gallon	4.03 ± 0.29 11 [2,3]	3.22 ± 0.24 16 [1]	2.67 ± 0.29 11 [1]	3.43 ± 0.55 8

[a]Mean ± standard error. [b]Number of data points. [c]Significantly different at $p < 0.05$ from 1-diesel, 2-diesel+trap, CNG, 4-CNG+TWC (Developed from data from Hesterberg et al. 2008).

(Tables 1 and 2). The exhaust-aftertreatment devices lower emissions for most compounds to similar levels in both diesel- and CNG-fueled buses. Hence, from a regulated and unregulated emissions standpoint, fuel choice offers no major advantage.

Particle Size and Number

In addition to regulated particle-mass emissions, air-quality regulators have shown a growing concern for particle size and number. Particular interest is focused on smaller particles in the ultrafine [<100 nanommeter (nm)] and nanoparticle (<50 nm) size ranges as they may present a greater health risk (Oberdorster et al. 1995; Seaton et al. 1995; Utell & Frampton, 2000). Several studies have compared emissions in terms of particle size and number (Holmen & Ayala, 2002; Holmen & Qu, 2004; Nylund et al. 2004; Thompson et al. 2004; Bose & Sundar, 2005; Nanzetta-Converse et al. 2005). The typical findings of Nylund et al. (2004) showed that diesel- and CNG-fueled transit buses equipped with exhaust aftertreatment (particulate filter and catalyzed muffler respectively) had 10-1,000-fold lower emissions of ultrafine particles and particles of other size ranges relative to diesel buses not equipped with exhaust aftertreatment (see Figure 1).

Figure 1 Particle-size distribution of emissions from diesel- and CNG-fueled transit buses (Nylund et al. 2004).

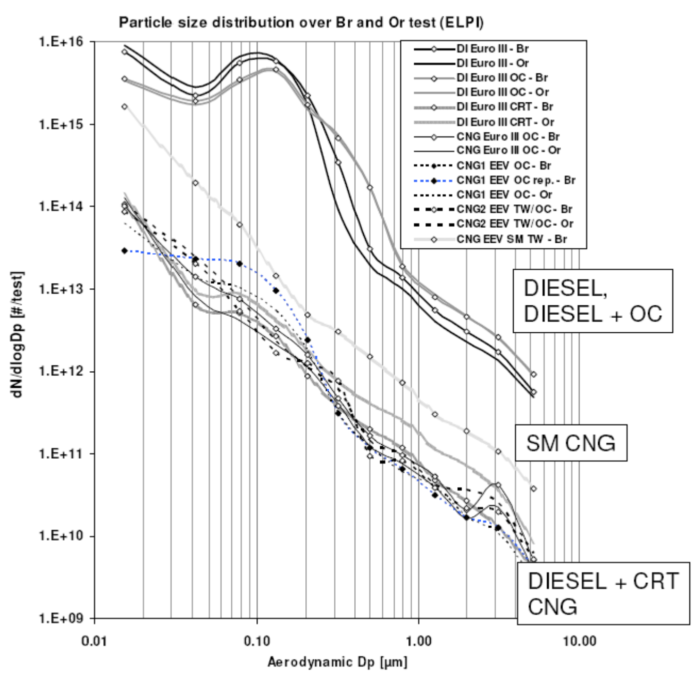

Table 2 Selected nonregulated emissions in transit buses (milligrams/mile).

Compound	Diesel	Diesel+Trap	CNG	CNG+Three Way Catalyst
Benzene	1.76 ± 1.54[a] 7[b]	0.41 ± 1.18 12 [3][c]	5.35 ± 0.94 19 [2]	0.00 ± 2.88 2
Ethylene	37.42 ± 120.6 7 [3]	3.35 ± 112.81 8 [3]	653.5 ± 96.2 11 [1,2,4]	0.00 ± 225.63 2 [3]
Propylene	2.66 ± 70.4 5	0.23 ± 64.31 6	184.08 ± 52.51 9	0.00 ± 111.39 2
Ethylbenzene	2.05 ± 0.74 4	0.09 ± 0.52 8	0.74 ± 0.37 16	1.36 ± 1.05 2
Toluene	0.33 ± 1.71 4 [3]	0.10 ± 1.21 8 [3]	4.79 ± 0.85 16 [1,2]	2.33 ± 2.41 2
Formaldehyde	59 ± 209 7 [3]	3.42 ± 175 10 [3]	1113 ± 148 14 [1,2,4]	0 ± 391 2 [3]
Acetaldehyde	27.91 ± 7.92 7 [2]	1.93 ± 6.63 10 [1,3]	37.28 ± 5.60 14 [2,4]	0.4 ± 14.82 2 [3]
Total 2-Ring Polycyclic Aromatic Hydrocarbons	7.200 ± 0.950 3 [2-4]	0.216 ± 0.623 7 [1]	0.385 ± 0.497 11 [1]	0.010 ± 1.170 2 [1]
Total 3-Ring Polycyclic Aromatic Hydrocarbons	0.650 ± 0.135 6 [2-4]	0.098 ± 0.105 10 [1]	0.102 ± 0.080 17 [1]	0.002 ± 0.234 2 [1]
Total 4- and Higher Ring Polycyclic Aromatic Hydrocarbons[d]	0.119 ± 0.026 6 [2-4]	0.10 ± 0.02 10 [1]	0.021 ± 0.016 17 [1]	0.000 ± 0.045 2 [1]

[a]Mean ± standard error. [b]Number of data points. [c]Significantly different at $p < 0.05$ from 1-diesel, 2-diesel+trap, 3-CNG, 4-CNG+TWC. [d]Fluoranthenes and pyrenes only (Developed from data from Hesterberg et al. 2008).

A California Air Resources Board (CARB) study noted that under certain test conditions, both diesel+filter and CNG-fueled buses had higher nanoparticle concentrations than the diesel without aftertreatment (Holmen & Ayala, 2002). This effect may be an artifact of the test conditions (Burtscher, 2005) and further research is needed to understand the significance of these findings. This ostensible problem may not be an issue, as recent research found that the latest model of diesel+filter aftertreatment devices readily removed nanoparticles from the exhaust (Kittelson et al. 2006).

An early particle-measurement study found that CNG-fueled transit buses had elevations of nanoparticles (Eastlake, 1999) and similar results were noted for liquefied natural gas (LNG) transit buses (Gautam et al. 2004). The source of the higher CNG nanoparticles was not identified, but oil consumption may play a role. Tonegawa et al. (2006) reported that improving oil consumption with better piston clearances, piston rings, and oil jets could reduce ultrafine and nanoparticle emissions in CNG engines. Alternatively, a recent study by Lanni et al. (2003) suggests that backfiring might explain the higher CNG-particle numbers. The addition of a catalyzed muffler (CNG+catalyst) to the CNG bus produced reductions in particle numbers to levels similar to the diesel+filter bus (Nylund et al. 2004). Finally, in a research application for a CNG bus, the combination of catalyzed particulate filter with a catalyzed muffler reduced particle numbers to ambient air levels (Gautam et al. 2005; Eaves, 2006; Gautam, 2006; Harris, 2006).

In summary, for vehicles equipped with new emission-control technology (diesels with catalyzed particulate filters and CNG with catalyzed mufflers), the numbers of particles, in all size ranges, in exhaust emissions are reduced similarly to levels 10-100 times lower than emissions levels from vehicles not equipped with exhaust aftertreatment. Thus, from the standpoints of emissions particle size and number, fuel choice seems to offer no major advantage.

Greenhouse Gas Emissions

The transportation sector is a major contributor of anthropogenic greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), methane, and nitrous oxide (N_2O). Emissions are compared by measuring GHGs in engine exhaust (tailpipe studies) or by estimating fuel-lifecycle GHG emissions using well-to-wheels (WTW) methodologies (e.g., Ahlvik & Brandberg, 2000; Beer et al. 2000; 2001; 2002; Brinkman, 2001; General Motors Corporation et al. 2001; Seguelong et al. 2003; Brinkman et al. 2005; Pont, 2007). To make comprehensive comparisons, analysts usually convert GHG emissions to their CO_2 equivalents and then sum them. Fuel-lifecycle studies contrast the emissions effects of production, transportation, and distribution activities in addition to actual end use in vehicles.

Several GHG-tailpipe studies did not find significant differences between diesel- and CNG-fueled vehicles (Northeast Advanced Vehicle Consortium, 2000; Davies et al. 2005; Hesterberg et al. 2008). Side-by-side comparisons of GHG emissions weighted for global warming potential (a value used to compare the abilities of different GHGs to trap heat in the atmosphere) found similar emissions for transit buses (Northeast Advanced Vehicle Consortium, 2000; Davies et al. 2005; Hesterberg et al. 2008) and refuse trucks (Davies et al. 2005; Hesterberg et al. 2008) (Table 3). While most of the methane in CNG fuel is combusted, a small portion of it is unburned and emitted in the exhaust. In terms of direct global warming potential, methane is 23 times more potent than CO_2 over a 100-year time horizon (Ramaswamy et al. 2001), but methane emissions contribute less than 10-20% of a CNG vehicle's emission-CO_2 equivalents, as much more CO_2 is emitted. Ullman et al. (2003) found that a diesel-school bus equipped with a catalyzed particulate filter had higher CO_2 emissions than a CNG bus. When a larger sample size was studied (18 diesel buses, 68 CNG buses), the results were less influenced by individual bus variability and the difference was not observed (Davies et al. 2005). Additionally, LeTavec et al. (2002) did not find an increase in CO_2 emissions from school buses that were retrofitted with traps. In passenger cars, CNG has lower vehicle lifetime CO_2 emissions for short trips (less than 160 kilometers), but higher emissions for longer trips due to lower fuel efficiency caused by their heavy fuel-storage systems (MacLean & Lave, 2000). Other factors that affect fuel efficiency, such as type of driving (stop-and-go versus cruising), will also affect CO_2 emissions.

Table 3 Greenhouse gas comparison in transit buses (in grams/mile).

Fuel Types	Carbon Dioxide	Methane	CO_2 Equivalents
Pooled Diesel (15)[b]	2965[a] ± 401	0.02 ± 4.96	2966 ± 479
Pooled CNG (22)	2587 ± 331	18.08 ± 4.09	2967 ± 395
	N.S.[c]	N.S.	N.S.

[a]Mean ± standard error. [b]Number of data points. [c]N.S. = Not significantly different at $p < 0.05$ (Developed from data from Hesterberg et al. 2008).

Most of the lifecycle analyses (LCAs) of GHG emissions evaluated in this review have found no significant difference between diesel- and CNG-fueled vehicles (see Table 4). A minority of studies reported either diesel or CNG to have lower GHG emissions. For example, two investigations found that CNG-transit buses had 21-53% more GHG emissions than diesel (Ahlvik & Brandberg, 2000; Seguelong et al. 2003), while two studies reported no significant differences (Beer et al. 2000; Silva et al. 2006). For the analyses where CNG-fueled vehicles had higher GHG emissions, the differences were mostly from higher CNG methane emissions, both from methane production and engine exhaust. While methane has lower carbon content than diesel fuel, this GHG advantage is eliminated by the higher fuel use required by CNG engines due to their lower fuel efficiency (Ahlvik & Brandberg, 2000). Similar conflicting results were found for heavy-duty trucks; some analyses reported that CNG heavy-duty trucks had lower GHG emissions on a distance-driven basis than diesels (Beer et al. 2000; 2001; 2002; Pont, 2007). The reasons for the conflicting results are not clear-cut, but may arise from differences in assumptions, LCA-model design, or model inputs and parameters.

In several LCA studies of light-duty trucks (Brinkman, 2001; General Motors Corporation et al. 2001; Brinkman et al. 2005) and passenger cars (Lave et al. 2000; MacLean & Lave, 2000; Jackson et al. 2003; Beer et al. 2004; Edwards et al. 2004; Unnasch, 2006), diesel- and CNG-fueled vehicles had similar GHG emissions. When looking at contemporary vehicles, diesel-passenger cars appeared to have lower GHG emissions (Pickrell, 2003; Toyota & Mizuho, 2004). Perhaps more relevant in the longer term, 2010 CNG vehicles had slightly lower GHG emissions with the main difference attributable to fuel production rather than engine emissions (Edwards et al. 2007; Farrell et al. 2007).

Table 4 WTW comparisons of greenhouse gas emissions between diesel- and CNG-fueled vehicles.

Vehicle Types	Diesel (gCO_2 eq/km)	CNG (gCO_2 eq/km)	Greater than 10% Different (higher vehicle)	Reference
Transit Bus	1759	1604	No	Beer et al. 2000
	2277	2070	No	Silva et al. 2006
	100%	121-142%	Yes (CNG)	Ahlvik & Brandberg, 2000
	1759	2277	Yes (CNG)	Seguelong et al. 2003
Heavy-Duty Truck	1656	1397	Yes (D)	Beer et al. 2000
	2018	1553	Yes (D)	Pont, 2007
Light-Duty Truck	298	311	No	General Motors Corporation et al. 2001
	261	261	No	Brinkman et al. 2005
Passenger Car	248	269	No	Beer et al. 2004
	166	166	No	Edwards et al. 2004
	161	171	No	Jackson et al. 2003
	52,000 CO_2 eq/lifetime	55,000 CO_2 eq/lifetime	No	Lave et al. 2000; MacLean & Lave, 2000
	227	233	No	Unnasch, 2006
	91 gCO_2 eq/MJ	68 gCO_2 eq/MJ	Yes (D)	Farrell et al. 2007
	166	145	Yes (D)	Edwards et al. 2007
	497	609	Yes (CNG)	Pickrell, 2003
	25% lower than gasoline	20% lower than gasoline	Yes (CNG)	Toyota & Mizuho, 2004

In summary, the majority of tailpipe and LCA studies found small or insignificant differences for GHG emissions from diesel- and CNG-fueled vehicles. Where some LCA studies report significant differences, equally credible LCA studies report otherwise. The differences probably arise from the inherent complexity of the quantitative models used to estimate emissions over the two fuels' life cycles (SAIC, 2006). Each study made different decisions on how to best model fuel production, transportation and delivery systems, and end-use emissions. In their guidance on interpreting LCAs, EPA noted

> [I]n some cases, it may not be possible to state that one alternative is better than the others because of the uncertainty in the final results. This does not imply that efforts have been wasted. The LCA process will still provide decision makers with a better understanding of the environmental and health impacts associated with each alternative. (SIAC, 2006).

Fire and Safety

Given the much greater flammability of CNG fuel compared to diesel fuel, it is important to determine if flammability and its impact on fire and safety should be a decision criterion when selecting a fuel. Despite the use of CNG fuel for several decades, this question has only recently been studied. In 2002, researchers compared the fire-safety risks associated with typical CNG and diesel school-bus systems including bus and fuel infrastructure (Chamberlain et al. 2002; Chamberlain & Modarres, 2005). Because historical data were not available for CNG buses, the researchers used probabilistic risk-assessment methodologies as practiced in the nuclear and aerospace industries. A fire fatality-risk index for CNG buses was developed to allow comparisons to historical diesel-bus data for the United States. The researchers examined risks associated with gas distribution, refueling, and operational and maintenance practices. The methodology then entailed determining the likelihood of risk scenarios by using fault-tree and event-tree modeling techniques along with generic data. Consequence analysis considered accident locations and lethalness from fires. The researchers estimated the subsequent effects on people located within a certain distance from such fires and determined total risk by summing the risk associated with each fire/accident scenario. The projected total fire-fatality risk for CNG buses was approximately 0.23 per 100-million miles of operation and 0.16 passenger fatalities per 100-million miles. While the CNG bus passenger-fatality risk was nearly 10 times lower than overall deaths from driving in the United States in 2007 (NCSA, 2009), it was 230 times higher than that for diesel buses. In addition, the total fire-fatality risk from diesel school-bus fires of 0.091 total fatalities per 100-million miles was 2.5 times lower than the CNG buses. Finally, for worst-case fire scenarios, CNG buses had much higher fatalities than diesel buses. Diesel-fueled vehicles thus are clearly superior from a fire- and safety-aspect.

Comparative Toxicity Studies

Mutagenicity

Mutagenicity is a measure of a compound's ability to cause permanent changes in the genetic information contained in living cells. Mutagenic compounds have been associated with adverse health effects such as cancer and birth defects. Emissions from diesel- and CNG-fueled engines contain mutagenic compounds (e.g., Lewtas, 1983; Gragg, 1995; Lapin et al. 2002). Lewtas (1983) first reported mutagenic activity in solvent extracts of diesel-particulate matter. Braun et al. (1987) found that natural gas combustion also produces mutagenic materials. In addition, the mutagenic compound dinitroflo-ranthene was found in diesel emissions and in incomplete combustion products of liquefied petroleum gas (LPG) (Nakagawa et al. 1987).

Prompted by these concerns, CARB conducted the first side-by-side comparison tests in 2001-2002 and these studies found that CNG-transit buses had mutagenic emissions 3-6 times higher on a mutations-per-mile basis than diesel+filter buses (Kado et al. 2005; Okamoto et al. 2006). The emitted particles from the CNG buses' emissions were 7-20 times more mutagenic than the emissions from the diesel+filter bus (Table 5). When CNG transit-bus exhausts were equipped with a catalyzed muffler, mutagenic activity was lowered, an outcome that suggests some of the mutagenic compounds were destroyed by the catalyzed muffler. However, the levels were still higher than diesel+filter (Okamoto et al. 2006).

Studies from Italy (Turrio-Baldassarri et al. 2004; 2006) and Finland (Nylund et al. 2004) found little or no mutagenicity in CNG-particulate emissions and higher mutagenicity in diesel emissions, the opposite trend observed in the CARB study. The difference may be due to the model year studied with the CARB CNG buses being the oldest. Recent improvements in CNG-aftertreatment devices may have resulted in more destruction of mutagenic compounds in the newer buses. Regardless, there are problems with overinterpreting mutagenicity test results (CARB, 2002). Mutagenicity tests provide an indication of potentially toxic compounds, but the results cannot be used directly to determine health risk. Because of this limitation, and the equivocal test results, mutagenicity potential may not be a useful fuel-selection criterion.

Table 5 Mutagenicity studies.

Fuel + Aftertreatment	Mutations/mg TA 98+S9	TA 98-S9	TA 100+S9	TA 100-S9
CARB Study (Kado et al. 2005; Okamoto et al. 2006)				
	Central Business District Test Cycle			
CNG no aftertreatment	27	50	12	8
CNG + aftertreatment	7.6	15	9.5	5.9
Diesel + filter	2.8	6.7	0	0
	Steady State (55 mph) Test Cycle			
CNG no aftertreatment	40	80	12	10
CNG + aftertreatment	28	37	23	8
Diesel + filter	25	51	9.6	7.3
	Urban Dynamometer Driving Schedule Test Cycle			
CNG no aftertreatment	37	73	13	6
Diesel + filter	6.9	8.8	6.8	2.5
	New York City Bus Test Cycle			
CNG no aftertreatment	19	39	5	15
Diesel + filter	3.5	11	0	0
VTT Study (Nylund et al. 2004)				
	Braunschweig Test Cycle			
Diesel + filter		1.1		
CNG + aftertreatment		0.2		

Acute Toxicity

There are limited toxicity data that provide direct comparisons between diesel- and CNG-fueled vehicles. Diesel-engine exhaust has been extensively studied over the last three decades, but CNG-engine emissions have only recently received similar attention. This disparity in data reflects public health concerns, the relatively greater use of diesel fuel, and the expense of toxicity tests. One recent study assessed acute toxicity of emissions from CNG, diesel, and gasoline vehicles in rat lungs (Seagrave et al. 2002; 2005). Lung responses to CNG were generally mild, with greater inflammation and cytotoxicity responses for the gasoline and diesel (no aftertreatment) samples. McDonald et al. (2004) found that equipping a diesel engine with a catalyzed particulate filter eliminated inflammation, cytotoxicity, tissue changes, and immune suppression. The reduction of emissions of compounds such as those listed in Tables 1 and 2 probably accounts for most of the reduced toxicity. While the diesel+filter and CNG results are not directly comparable because of different engine sizes and sample collection conditions, the data suggest that acute toxicity of engine emissions would be similar between CNG vehicles equipped with exhaust aftertreatment and new technology diesel.

Economics Studies

Diesel, with its established refueling infrastructure, has a distinct economic advantage over CNG-fueled vehicles (Toy et al. 2000). CNG vehicles are more expensive to buy, US$320,000 compared to US$270,000 for a diesel-transit bus (Cannon & Sun, 2000; Eudy, 2002). Infrastructure changes for refueling stations can cost US$900,000 to US$5,000,000 and depot-modification costs can run US$300,000 to US$15,000,000 (Cannon & Sun, 2000; Watt, 2000; Eudy, 2002; Hunt, 2002; Barnitt & Chandler, 2006). The lack of an adequate refueling network, driven by the costs of building such a system, has hampered CNG development (Di Pascoli & Aldo, 2001; NREL, 2001; Chandler et al. 2002).

New York City Transit conducted a cost-comparison study based on its operating experiences with diesel- and CNG-fueled buses (Lowell et al. 2003). The agency found costs to be six times greater for CNG-transit buses compared to diesel+filter buses (annualized net present value of total costs for 200 buses at one depot: US$2,300,000 vs. US$300,000). The main contributors to the higher CNG costs include "increased capital costs for purchase of buses and installation of fueling infrastructure, and increased operating costs for purchase of fuel, bus maintenance, and fuel station maintenance." Infrastructure changes included construction of a natural gas-fueling station and safety modifications of the bus depot (e.g., methane detectors, increased ventilation, removal of ignition sources). These costs may represent the high side as construction is more expensive in New York City than in most other parts of the country.

Cohen et al. (2003) estimated the incremental cost effectiveness of diesel- and CNG-transit buses relative to conventional diesel in the United States. The researchers calculated cost effectiveness as the ratio of acquisition and operating costs over health losses. Health losses (death and disease) were due primarily to particulate matter and ozone exposures. Cohen et al. (2003) found that while CNG provided 50% more health benefits per bus, the diesel bus was 5-8 times more cost-effective due to its lower costs. However, in school buses, CNG and diesel+filter buses had similar health benefits per bus, but the diesel+filter buses were 10 times more cost-effective because of their lower costs (Cohen, 2005). In commenting on Cohen et al. (2003), McClellan & Lapin (2003) observed that instead of using the same funds to upgrade a transit-bus fleet to CNG, one could get 6 times more particulate-emission reductions with the diesel+filter option. This outcome is because the additional costs of buying CNG buses are much greater than diesel+filter buses so a transit company can afford to replace more of its fleet with cleaner buses using the diesel+filter option. Furthermore, they noted that since budgets for the purchase of new buses are regularly subject to tight constraints, and because newer (post-2007) CNG and diesel buses both have similarly very low emissions, fleet managers should give extra emphasis to the added costs of buying CNG buses. Such circumstances favor diesel over CNG based on this selection criterion.

In contrast to Cohen et al. (2003), Johansson (1999) found that in Europe CNG had a cost-effectiveness advantage in urban settings, while diesel, with lower infrastructure costs, was more cost effective in rural settings. Some of the differences between the two studies may reflect regional difference between the United States and Europe. More importantly, Johansson did not use emission factors that reflect emission reductions achieved with current diesel particulate-filter technology. Schubert & Fable (2005) found no differences in the future lifecycle costs of diesel and natural gas heavy-duty engines for refuse haulers, transit buses, and short-haul trucks. The main shortcoming of the Schubert & Fable study was that it did not evaluate the far greater infrastructure costs for CNG.

In summary, diesel vehicles have a distinct cost advantage over CNG vehicles. For a given budget, more diesel+filter vehicles can be purchased providing more emissions reductions when older, higher emitting vehicles are replaced.

Operational Issues

The main operational issue with CNG vehicles is their lower fuel economy [i.e., miles per gallon (mpg): transit buses by 16%–25% (Barnitt & Chandler, 2006; Chandler et al. 2006), tractor-trailers by 23% (Lyford-Pike, 2003), and delivery trucks by 27% (Chandler et al. 2002)]. The lower energy content of CNG fuel, the extra weight of the CNG-fuel tanks, and the lower efficiency of CNG engines contribute to the lower fuel economy of CNG vehicles (Pelkmans et al. 2002).

Given the lower fuel economy for CNG, it is not surprising that for early transit-bus fleets road calls were higher for CNG buses, mostly for fuel-system problems including running out of fuel (Motta et al. 1996). Improvements in engine design and better bus-driver training and awareness seem to have alleviated this problem, as recent CNG transit-bus fleets experienced 16-44% more miles between road calls than their diesel counterparts (Barnitt & Chandler, 2006; Chandler et al. 2006).

Maintenance and operating costs vary and give a mixed picture of CNG- versus diesel-fleets. In some cases, maintenance costs were 15–29% higher for CNG vehicles (replacement of spark plugs, spark wires, and fuel regulators and repairs of clutches and transmissions) (Chandler et al. 2002; Hunt, 2002). However, in another study maintenance was 12%

lower for CNG vehicles (Chandler et al. 2006), probably due to better preventative maintenance. The age of the buses is important, as older CNG buses need to adhere closely to preventative maintenance schedules to avoid significant emissions degradation (Hunt, 2002).

As with maintenance costs, UPS's Hartford fleet reported total operating costs (including fuel and maintenance costs for running the trucks in service, but not including driver-labor costs) that were 19% higher for CNG vehicles (Chandler et al. 2002). This fleet consisted of early production models that had problems with spark plugs, spark wires, and fuel regulators. For the Washington Metropolitan Area Transit Authority, total operating costs for CNG buses were similar to diesel vehicles (Chandler et al. 2006). Interviews with 42 transit agencies identified training, fueling infrastructure, commitment to the CNG program, and public support as critical to successful operation of CNG fleets (Eudy, 2002).

In summary, the main operational issue with CNG vehicles is their 16–27% lower fuel efficiency. Operating and maintenance costs are variable with no consistent difference between diesel- and CNG-fueled vehicles.

Summary

We reviewed data potentially useful to choosing the most beneficial fuel, including data on emissions, fire and safety, toxicity, economics, and operations. Table 6 summarizes these observations. Diesel- and CNG-fueled vehicles with the latest emission-control technology, including engine-exhaust aftertreatment, have very similar emissions of regulated and unregulated compounds and particles through all size ranges. Likewise, GHG emissions, measured at the tailpipe and estimated over the fuel lifecycle, are similar. In addition, no important toxicity differences were reported. While operating and maintenance costs are variable, with no consistent differences between diesel- and CNG-fueled vehicles, CNG vehicles are less fuel-efficient. Significant infrastructure costs are involved with implementing a CNG fueled-vehicle fleet, potentially limiting availability of funds for vehicle replacement. Finally, diesel vehicles have a distinct fire- and safety-advantage over CNG vehicles. The selection factors with the clearest differences are thus infrastructure costs and fire and safety concerns, and these are much greater for CNG fuel. These considerations should be part of the decision-making process when selecting a fuel for a transportation system.

Table 6 Summary of the comparisons between CNG and diesel fuel vehicles.

Potential Selection Criteria	CNG vs. Diesel
Emissions	
Regulated & nonregulated compounds	Equivalent
Particle size and number	Equivalent
Greenhouse gases	Equivalent
Fire & safey	Diesel better
Toxicity	
Mutagenicity	Equivalent
Acute toxicity	Equivalent
Economics	Diesel better
Operations	Equivalent
Operating & maintenance costs	Equivalent
Fuel Efficiency	Diesel better

Authors' Note

Thomas Hesterberg and William Bunn are employed by Navistar, a major manufacturer of diesel engines and vehicles. Charles Lapin is a consultant to Navistar. All authors declare no other financial interest in the subject matter of this study. Results and conclusions presented in this paper were drawn independent of the interests of the sponsor.

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ARTICLE

Toward a typology for social-ecological systems

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Characterizing and understanding social-ecological systems (SESs) is increasingly necessary to answer questions about the development of sustainable human settlements. To date, much of the literature on SES analysis has focused on "neat" systems involving a single type of resource, a group of users, and a governance system. While these studies provide valuable and specific insights, they are of limited use for application to "messy" SESs that encompass the totality of human settlements, including social organization and technologies that result in the movement of materials, energy, water, and people. These considerations, in turn, create distribution systems that lead to different types of SESs. In messy SESs the concept of resilience, or the ability of a system to withstand perturbation while maintaining function, is further evolved to posit that different settlements will require different approaches to foster resilience. This article introduces a typology for refining SESs to improve short- and long-term adaptive strategies in developing human settlements.

KEYWORDS: vulnerability, human settlements, social organization, resource management, local communities

Introduction

Over the past twenty years, a growing community of practice has treated human and biophysical systems as linked and has characterized them as constituting social-ecological systems (SESs), that is as complex, integrated systems of humans within the ecosystem (Berkes & Folke, 1998; Holling 2001; Colding et al. 2003; Anderies et al. 2004; Forbes et al. 2004; Adger et al. 2005; Young et al. 2006; Smith & Stirling, 2008; Walker & Lawson, 2009). An SES is comprised of feedbacks among human values, perceptions, and behaviors and the biophysical components of the ecosystems in which people live, resulting in a "resilient" or "vulnerable" trajectory trending toward sustainability or collapse (Gallopin, 2006). However, when technology is factored in, these feedbacks result in markedly different outcomes depending on the type of SES.

A growing body of literature (e.g., Ostrom, 2007; Resilience Alliance, 2007a; 2007b) examines the management of SESs, but treats them as "neat" systems in which humans and their resources are reduced to "blocks" representing subsystems with simple and relatively clear flows (Anderies et al. 2007). Neat SESs in this context deal with a well-defined (often single) resource, a group of users of this specific resource, and a set of common-pool resource governance systems. This emphasis on neat SESs makes it difficult to accommodate an associated sociotechnical regime (Smith et al. 2005) and often leads to recommendations that are difficult for the majority of sustainability practitioners to translate. We argue for the need to move away from the idealized concept of "neat" SESs and to develop the concept of "messy" SESs involving the simultaneous use of multiple resources by diverse users and the technologies they employ. Such a viewpoint can more readily accommodate the inherent complexity of SESs than strictly neat SESs. For example, an SES comprising a village in northwestern Alaska and the subarctic tundra landscape in which it exists (e.g., Alessa et al. 2008) is subject to the seasonal and cyclic availability of subsistence species (e.g., salmon, caribou, moose, walrus, seal), the consequences of regional, national, and global economies, and global climate-change effects on precipitation and temperature—to name just a few of the SES dynamics at play in this particular case.

The Need for a Typology of Messy SESs

As a first step in the challenging task of moving toward messy SESs, we propose that different messy SESs can be distinguished into ideal types that reflect combinations of the inherent robustness of natural resources (i.e., water, food, and materials), social organization (including policies), and infrastructure/technology that contribute to efficiency (e.g., transportation). Diverse disciplines use typologies (Winch, 1947; McCullough, 2001; Morillo et al. 2003) and

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this article adopts this methodology to move from an abstract concept to a practical application. The proposed classification is a continuum along which human settlements can be typed rather than a strict taxonomy with clear and well-defined boundaries. We believe this approach will help to develop strategies that better promote adaptation to change in diverse settings. The types presented here are intended to be neither exhaustive nor prescriptive; rather, they are offered as a demonstration of what a typology for messy SESs might look like, acknowledging that the concept will require further development.

An Initial Framework for Messy SES

We organize our typology along a continuum of community size, reflecting ecosystem productivity, social organization, and responsiveness (or adaptability) to maintain resilience or a resilient trajectory (in which a settlement's actions will eventually lead to resilience). The three scales used accommodate differences in sociometabolic and land-use transitions (Kraussmann et al. 2008; Nuissl et al. 2009) associated with a coarse differentiation between city-, town-, and village-level settlement sizes, ranging from high-density to low-density urban structures (Figure 1). The size continuum is based on the central idea that both size and scale matter and that the way an SES is viewed and managed will, in part, reflect this parameter. The second continuum is meant to capture the responsiveness of the SES to its current trajectory (Walker & Meyers, 2004): trending toward resilience, a transitional state at a threshold that could move either toward resilience or vulnerability, or a condition of vulnerability or even collapse (Figure 1). Thus, in the extremes, a large community with ineffectual social organization located in a natural resource-poor area will be the least resilient and a smaller, more effectively organized one situated in a resource-plentiful area will be the most resilient. Between these two poles are many types of settlements that will possess features that result mainly in a trajectory toward one type or the other. Understanding all types is important since we can learn why some settlements are comparatively resilient, even when resources are relatively scarce, and recognize which interventions will be more or less worthy of investment.

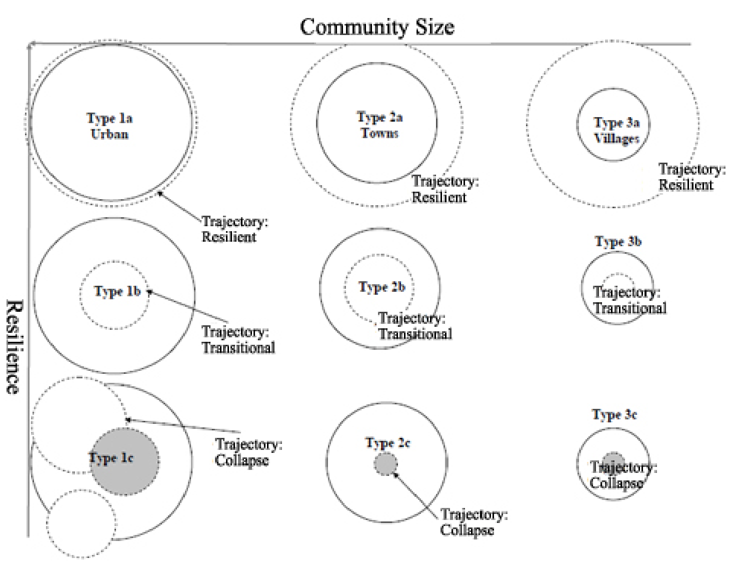

Figure 1 Framework for messy social-ecological systems.

Social-Ecological Systems

Approaches to describing and analyzing SESs include concepts of robustness (e.g., Anderies et al. 2004), resilience (e.g., Walker & Lawson, 2009; Walker & Salt, 2006), thresholds (e.g., Walker & Meyers, 2004), vulnerability (e.g., Gallopin, 2006), sustainability (Kajikawa, 2008), human settlements (United Nations-Habitat, 2007), sociometabolic transitions (e.g., Krausmann et al. 2008), sociotechnical systems (Smith & Sterling, 2008), and land-use transitions (e.g., Nuissl et al. 2009).We define a resilient SES as one that can meet its needs and desires within the means of its local environment, where "local" reflects variable scalability relative to the geography surrounding a settlement, and possesses a trajectory consistent with maintaining this condition over long time periods. While this is an idealized definition, since it is problematic that any modern city or town can be wholly resilient or even completely dependent on its local environment, it provides a basis for a relative scale of resilience in SESs, allowing the identification of cities or towns that possess greater resilience and others that possess greater vulnerability. It is also a provisional, simplified definition that is a starting point for understanding "messier" conditions.

In their simplest form, types of SESs can be organized based on the ability to acquire, distribute, and sustain access to natural resources over long intervals through tradeoffs that maintain a dynamic and flexible equilibrium between social and ecological well being (Colding et al. 2003). Additionally, the ability for settled communities to mitigate unexpected exogenous events is important in determining resilience. To define these measures, we use the notion of access to designate resources in close proximity to a community *or* for which there is sufficient means to either extract or import the resources. The ability to distribute resources implies the capability for institutions to function more or less efficiently and equitably so that needed or desired resources move to individuals and households, and for communities to regulate when a given resource is available (Anderies et al. 2007). Exogenous events in this case represent outside social-ecological occurrences over which a community has little or no direct control, but to which it can respond and mitigate undesirable outcomes. Resources, in this case, are defined as goods and services intended to enhance a community's quality of life regardless of any waste (Rogerson, 1995). This feature reflects the fact that while all societies seek to meet their needs and desires, there are several SES types in which basic human needs remain unmet and which incur the impact of distant resource supplies. The importance of understanding what type of messy SES a practitioner is assessing is critical in developing appropriate strategies that promote resilience in a timely fashion.

Sociometabolic transitions refer to the dynamics of material and energy flows in a society over long periods (Geels, 2005; Krausmann et al. 2008) and provide a mechanism for considering SESs. While broad transitions in energy flows—for example from an agrarian to an industrial society—can indicate different levels of sustainability, the trajectory of an urban center's socioeconomic metabolism, such as decreasing consumption of fossil fuel, may contribute toward resilience in a SES.

SES types have been conceptualized as the interactions between social institutions and biophysical dynamics. For example, a subset of social-biophysical interactions in SES types are ecological-economic systems that describe human activity involving the joint interaction of ecological (e.g., soil fertility) and economic (e.g., commodity prices) factors affecting commercial and agronomic facets of modern food production (Batabyal & Yoo, 2007). However, in reality many SESs at the extremes of the continuum should be considered as social-technological systems (Smith & Stirling, 2008). As an example, a city with rapidly growing squatter settlements may be in the process of building permanent subsidized housing to manage the consequences of uncontrolled human waste (i.e., disease vectors), thus moving itself toward a more resilient state, but this characterization holds true only if there are adequate water resources and treatment technologies. Conversely, a city may experience rapid immigration from rural areas with no plans or means to address the consequences of population growth, thus moving the SES toward vulnerability.

In conceptualizing the SES typology, we assimilated a diverse body of knowledge relevant to resilience and sustainability including the following:

- Inherent productivity and vulnerability to catastrophic events in ecosystems on earth (e.g., Adger et al. 2005)
- Land use and land-cover change (e.g., Lambin et al. 2003; Nuissl et al. 2009)
- Rapid changes observed under global environmental stress (e.g., Alley et al. 2003)
- Institutions and governance of natural resources (e.g., Ostrom, 2005; Armitage, 2008)
- Migration and demographic structure (e.g., Adger et al. 2002; Berkes et al. 2003)
- Cooperative and adaptive management (e.g. Carlsson & Berkes, 2005; Armitage et al. 2007)
- Perceptions and awareness of change in water resources (e.g., Alessa et al. 2007)
- Socio-technological regimes (e.g., Smith & Stirling, 2008)
- Socio-economic metabolism (e.g., Krausmann et al. 2008).

A Typology of Messy SES

The framework for the SES typology (Figure 1) is refined by incorporating diagnostic or indicator variables (Table 1) that provide an aggregate determination of the resilience trajectory for a particular SES. These variables are derived from resilience frameworks (Ostrom, 2005), resilience case studies (Walker & Lawson, 2009), socio-metabolic transition frameworks (Krausmann et al. 2008), and land use transition frameworks (Nuissl et al. 2009). Each indicator is represented as a binary value, high or low, and in the examples given (Table 2) is reached using the Delphi technique (Rowe & Wright, 1999) as a means for obtaining a reliable consensus by a panel of resilience practitioners (including biological, physical, and social scientists) using a series of questionnaires with controlled feedback. The Delphi technique is a method for structuring information derived from a group of experts and developing consensus on the best available knowledge to deal with a complex problem. Where possible, a quantitative measure for each indicator is used to provide consistency and robustness. For example, we base variability in resource availability on OECD (2007) environmental data for water demand, accessibility, and potability. Communication is a measure of the connectivity of an SES and is based on the connections and strengths of global network links that rate cities around the globe within economic and communication networks (Derudder et al. 2003). We predicate risk to an SES due to natural hazards upon the ranking of cities around the globe based on their exposure to coastal flooding, storm surge, and high wind damage (Nicholls et al. 2008).

For each scale (city, town, village), an SES is categorized as Type A (resilient) where the majority of indicators (8 of 10) are high, as Type C (vulnerable) where the majority of indicators (8 of 10) are low, and as Type B (transitional or mixed) where the indicators are neither predominantly high nor low. In addition to the overall categorization of SESs (Figure 1), the variables that each indicator describes (Table 1 and 2) provide diagnostic value for understanding messy SESs. However, we caution that this is a provisional framework and it will require significant input from a diverse community of practitioners to evolve and improve. It is also a relative rather than an absolute scale, so that a city or town that is categorized as Type A (resilient) is relatively resilient compared to a Type B or Type C city or town.

Type 1 Division

Resilient Cities (Type 1a)

Type 1a SESs are in large urban areas comprised of either high- or low-density urban structures, primarily cities and metropolitan regions in which both inherent per capita resource supply and the institutions that facilitate access to those resources are quantitatively and qualitatively robust (Table 2). Type 1a SESs may provide insights to successful resource strategies, but they are typically the least challenging sites from a global resilience perspective. These SESs have enough social diversity (e.g., in values, institutions, and control) to initiate and maintain collective action, but not so much heterogeneity as to impede it over time (Heckathorn, 1993). Highly efficient and accessible transportation infrastructure enables easy access to and distribution of particular resources (Ardekani, 1992). A high degree of resource substitutability (e.g., multiple local and distant water supplies) enables Type 1a SESs to have greater and easier access to critical resources by creating resource redundancy.

Proactive management by institutions enables cities to have diversified economies (i.e., not dependant on one or a few economic sectors), as well as mixed use of natural resources from proximate hinterlands (Grant, 2005). Effective institutions are often critical in the mitigation of exogenous events. A key example of this capacity is successful control and management of floods by local government to lessen economic disruption and social impact (Plate, 2002).

Table 1 Features used to develop an initial typology of messy SESs and their links to the Institutional Analysis Development (IAD) Framework.

Feature	Components	Links to IAD Framework
Size	Boundaries	RS2–clarity of system boundaries RS3–size of resource system U1–number of users
Diversity	Social capital; land use; cultural integrity	GS4–property rights system RU1–resource unit mobility U6–norms/social capital
Distance	Resource use zone extension	U9–technology used RU3–interaction among resource units RU4–economic value RU7–spatial & temporal distribution
Retention	Efficiency (e.g., recycling)	RS5–productivity of system U5–leadership/entrepreneurship
Distribution	Equity, infrastructure	GS7–consititutional rules RU7–spatial & temporal distribution UP–technology used
Persistence	History, rigidity	U3–history of use U8–dependence on resource
Collectivism	Governance systems	GS1–government organizations GS2–nongovernmental organizations GS6–collective-choice rules
Variability	Location	RS9–location of resource system U4–location of users
Directionality	Import versus export	RU2–growth rate of resource RU4–economic value of resource RU7–spatial & temporal distribution
Substitutability	Control; range of goods and services' total costs	U5–leadership/entrepreneurship U6–norms/social capital
Communication	Diffusion of knowledge, decision making	GS5–collective-choice rules
Risk	Social, ecological	U6–norms/social capital

Table 2 Typology of messy social-ecological systems.

	Resilient			Mixed			Vulnerable		
	1a	2a	3a	1b	2b	3b	1c	2c	3c
Indicator	**Vancouver CAN**	**Nishio JPN**	**Ganges CAN**	**Sao Paulo BRA**	**Al Qamishli SYR**	**King Cove USA**	**Dhaka BGD**	**Kati MLI**	**Vaiaku TUV**
Diversity (land use)	High	High	High	Low	High	Low	Low	Low	Low
Distance (proximity to nearest source)	High	High	Low	Low	Low	High	Low	Low	Low
Retention (resource efficiency, e.g. mass transit)	High	High	High	Low	Low	Low	Low	Low	Low
Distribution (high-density, low socio-economic housing)	High	High	High	Low	High	High	Low	Low	Low
Persistence (limited or low net migration)	High	High	High	Low	High	Low	Low	Low	Low
Collectivism (public versus private institutions)	High	Low	High	High	High	High	Low	Low	High
Variability (e.g., water demand, availability, and potability)	High	High	High	Low	Low	High	Low	Low	Low
Substitutability (e.g., water sources)	High	High	High	High	High	High	Low	Low	Low
Communication (e.g., global connectivity)	High	High	High	High	Low	Low	Low	Low	Low
Risk (e.g., flood prone)	High	Low	Low	High	Low	High	High	Low	High

Vulnerable Cities (Type 1c)

Type 1c settlements reflect a serious challenge facing humanity: that of growing urban areas consisting mostly of poorly educated, impoverished residents, many of whom have immigrated from rural areas to pursue a higher quality of life through better employment or due to displacement from conflict and/or climate change (United Nations-Habitat, 2007). We anticipate that, with the increased frequency of environmental catastrophes, particularly in low-lying coastal areas, this SES type will become increasingly dominant and should be given special attention. These communities have relatively low resource access, limited collective institutions to acquire resources for the population, and a chronic inability to control the timing or volume of resource use. Vulnerability to exogenous events further limits the resilience of this type of SES; for example, poor roads or limited accessibility to food sources hinder settlement recovery from major disasters (Forbes et al. 2004). Adaptation strategies developed by communities or governments in this SES type must first address basic human needs before establishing approaches that involve cooperative institutions and innovative technologies. Because of this situation, Type 1c SESs must be considered differently from, for example, Type 1a or 1b SESs, where such approaches can variously address institutional dynamics and easily absorb risks of failure or trial-and-error. This distinction is important because interventions (e.g., aid) that maintain such SES differentiation are not simply mechanical processes; their potential withdrawal carries enormous emotional, moral, and political consequences. Additionally, the underlying circumstances that encourage the development of Type 1c SESs are often extremely complicated in their origins (e.g., resource extraction or manufacturing for first-world countries that diminishes or restricts indigenous access to critical natural resources), but simple in their outcomes (e.g., extirpation of local communities through migration).

Mixed Resilient/Vulnerable Cities (Type 1b)

Type 1b SESs reflect the heterogeneity of many high-density settlements around the world. Geographic domains or neighborhoods often exhibit properties of either Type 1a or Type 1c, but exist within the same political unit (e.g., a municipality). Such types are extremely complex and may require the most innovative strategies because the potential for conflict is enormous and the dynamics of local crises (e.g., riots), collapse, and response are extremely unpredictable.

Settlements of this type are highly divergent in access, distribution, and control of resources. These cities can respond effectively in some areas to exogenous events such as weather-related disasters, but the response is often uneven and large segments of the population—although not the overwhelming majority—receive inadequate assistance (e.g., New Orleans and Hurricane Katrina). Much of this divergence depends on the socioeconomic levels of the area and the disparity between resource availability and allocation. The quality and effectiveness of services vary greatly in these types of cities, even if institutions are well developed. Such urban districts have population segments that are resilient to certain social-ecological changes, whether drastic or subtle, but other segments are far less resilient. One such city is New Delhi, in which roughly 30% of the population did not have access to safe water in the late 1980s, leading to the widespread propagation of waterborne diseases (Table 2; Pelling, 2003). Included in Type 1b SESs are the periurban transition or tension zones that persist in the vicinity of large metropolitan regions–most prevalent in developing countries. In the typology, these districts could be treated either separately as peripheral areas or in conjunction with metropolitan areas as center-periphery complexes.

Type 2 Division

Resilient Towns (Type 2a)

Settlements characterized as Type 2a are towns (i.e., urban areas smaller than cities) that are able to adequately access, distribute, and control resources. Exogenous events affect these settlements, but in ways that are relatively minor or can be quickly mitigated. In terms of their characteristics, these locales are very similar to Type 1a cities. For instance, many of these communities have adequate infrastructure, a relatively diverse economy, mixed land uses, and substitutability or redundancy in the distribution and provision of resources (Table 2). Also, institutions are well established in Type 2a SESs, providing for a good level of resource control and response to exogenous events.

In addition to being smaller than cities, Type 2a towns have relatively low emigration rates. For example, in Western Europe rural migration from small towns into large cities slowed significantly at the end of the industrial revolution in the nineteenth century (Hochstadt, 1998). Type 2a towns are relatively self-sufficient within their regions and use many local goods and services. Some of these communities have developed mechanisms for autonomous government and depend on local agriculture (Day, 1998). Such indicators show less dependence on economic and sociopolitical activities than other towns and cities.

Vulnerable Towns (Type 2c)

Similar to Type 1c cities, Type 2c towns have a chronic inability to access, distribute, and control resources. Exogenous social-ecological events can have very acute consequences in these settlements, which often display poor infrastructure, weak institutions, and a low level of redundancy in resource use (Table 2). Unlike Type 2a towns, these communities lack characteristics that make them self-sufficient. Rather, many of these locales depend on goods and services from major cities or other resource providers. These settlements generally have low economic and land-use diversity, depending often on only a few core industries and land-use functions (Hinderink & Titus, 2002). Many inhabitants are transients who migrate to the town for short periods (Roberts, 2001). Type 2c SESs often have a legacy of rapid environmental degradation due to the types of industries or livelihoods that support them. Particularly challenging is the potential loss of cultural diversity, and hence adaptability, especially when Type 2b SESs choose to adopt land-use and economic activities that cannot be sustained over long periods.

Mixed Resilient/Vulnerable Towns (Type 2b)

Type 2b towns, similar to Type 1b urban areas, possess characteristics of both Type 2a and 2c SESs. However, the scale of social functions for these settlements is more constrained, thus affecting the strategies that they might adopt. Some areas of these settlements show capabilities in obtaining, distributing, and controlling resources, as well as in mitigating exogenous social-ecological events. Institutional infrastructure and capabilities are generally mixed, with some areas or population segments getting better service (Table 2). Many Type 2b towns were built to extract specific resources such as coal or oil. These towns can have successful economies, as occurred in Brazil in the late 1980s, but large segments of the population are migratory workers and/or low-wage earners dependant on undiversified land use and economies (Godfrey, 1990). These characteristics show aspects of social and ecological resilience, but are threatened by degradation in the undiversified economic and ecological resources on which they depend (Ryder & Brown, 2000). However, unlike Type 1b cities, Type 2b towns generally have greater familiarity and connectivity within and between social networks, partially due to their smaller scales. Thus, approaches that address these aspects of social-ecological phenomena are more likely to produce desirable outcomes than in Type 1b cities.

Type 3 Division

Resilient Villages (Type 3a)

This settlement type represents villages that have good access, distribution, and control of resources, and the capacity to respond to external social-ecological events. Such villages may display some similarities to large towns with relatively well functioning institutions and effective resource management (Table 2) that sustain ecosystem services in the long term. One distinguishing characteristic of these communities is that they are reasonably self-sufficient in basic resources (e.g., food and water) and can easily exchange or obtain nonessential resources (e.g., mechanized equipment). These villages exhibit some redundancy with respect to the sourcing of basic resources, for instance having rotating agricultural field systems and crops or being able to hunt several species in multiple areas. Residents in such communities do not emigrate at high rates, preserving local knowledge that enables these villages to perpetuate skills useful for resilience practice. Examples of such communities include Amish settlements in the United States (Zook, 1994) and some *kibbutzim* in Israel (Ben-Rafael, 1997). The argument can be made that of all the SES types, these settlements are the most robust at adapting to social-ecological changes caused by internal community needs (e.g., water and food demand), but are not as resilient as Type 1a cities to exogenous events. For example, Type 3a villages may not have adequate medical facilities, resources, and personnel to deal with a pervasive disease or with large-scale disasters such as earthquakes.

Vulnerable Villages (Type 3c)

Showing a near total lack of basic resource allocation, distribution, and control, Type 3c villages are typically found in impoverished areas and may survive primarily on outside aid (Table 2). They are very susceptible to outside social-ecological events that can induce collapse or outright destruction. Typical characteristics of these settlements include high rates of emigration to urban centers, dependence on outside goods and services, poor infrastructure, and chronic to acute resource shortages. Type 3c villages can be found in rural Botswana and in the Democratic Republic of the Congo (Mbenza, 1995; Tesfaye & Asefa, 1999).

Mixed Resilient/Vulnerable Villages (Type 3b)

Villages of this type display characteristics of Type 3a and Type 3c. They have adequate access, distribution, and control of some critical resources. Some resilience to exogenous events is also evident. Such communities, however, are often limited in resource quantities and in their capacity to distribute goods and services. Vital resources such as water are often difficult for households in Type 3b villages to obtain locally or are in short supply, hindering resource self-sufficiency (Table 2). The economies of these communities often depend upon one or a few primary sectors. These characteristics promote vulnerability, particularly if resources are disrupted or there is significant change in the regions' economic role. Examples can be found in Alaskan villages that have a heavy dependence on undiversified resources (e.g., salmon for food), as well as oil for heating, transport of goods, and local travel to obtain subsistence food (e.g., by snow machine, all-terrain vehicle, boat, or small airplane) (Ellanna & Wheeler, 1989). Included in Type 3b divisions are low-density agroforestry or horticultural landscapes.

Discussion

Using tenets from the SES typology (Figure 1) and components of the messy SES types outlined above (Table 2), we set out some generic characteristics for each SES type (Table 3). In this framework, collectivism constitutes the ability to recognize past successes and failures, including rigidity, and to alter institutions, built environments, and technology to avoid future failures and to optimize successes. Social networks constitute functional affiliative and familial ties and are most intact in Type 3a SESs with limited immigration and emigration. Functional diversity, response diversity, and exposure to catastrophe (disaster versus seasonal events such as monsoons) reflect a type's stability. For example, a Type 1a SES is fairly stable due to sustained equilibria across components and scales (e.g., socialized services, regulated minimum wages, diverse supplies of food, plentiful water) whereas a Type 1b SES appears stable, but has clusters or zones prone to vulnerability (e.g., socioeconomically disadvantaged neighborhoods that can rapidly develop acute resource shortages requiring external aid or discontent leading to social unrest, even riots). Variability reflects the possibility of emergent social and physical structures such as hierarchies, novel policies, and coupled sociotechnological interventions. Substitutability reflects a settlement's social and ecological wealth. Social capital includes knowledge and capacity for innovation and is generally higher in SES types where basic human needs (e.g., water and sanitation) have been met. Rigidity reflects the inability of settlements to adapt physically and socially to changing conditions, especially if unexpected. An example is

Table 3 Characteristics of messy SES types.

	1a	1b	1c	2a	2b	2c	3a	3b	3c
Diversity	●	●	○	●	●	○	●	○	○
Distance	●	○	○	●	○	○	●	●	○
Retention	●	●	●	●	●	○	○	○	○
Distribution	●	●	●	●	○	○	○	○	○
Persistence	●	●	●	●	●	●	○	○	○
Collectivism	●	●	●	●	●	●	○	○	○
Variability	●	●	●	●	●	●	○	○	○
Substitutability	●	●	○	●	●	○	●	○	○
Communication	●	●	●	●	●	●	○	○	○
Risk	○	○	○	○	○	○	●	●	●

● Higher levels, plentiful, well developed, and so forth.
○ Lower levels, scarce, poorly developed, and so forth.

built environments engineered to serve multiple purposes or tolerate extreme ranges of conditions and, on the social side, norms and cultures that accept uncertainty and instability as manageable.

We speculate that five general propositions will arise from this typology, building upon Walker et al. (2006). First, size matters. Smaller settlements in resource-rich areas, despite having less social capital than larger SES types, have a stronger ability to supply basic needs and are often highly resilient (Type 3a), but with increasing size social capital allows settlements to produce and acquire resources from broader scales that may approach global scope. However, the tradeoffs in social resilience, such as decreased dependence and awareness of geographically local environments, may result in vulnerabilities that are only acutely realized when marked change (e.g., a natural disaster) interrupts supplies (Type 1a). In other cases, the opportunities perceived to exist in larger settlements can result in vulnerabilities, for example, rapid regional immigration leading to water shortages and disease spread that becomes difficult to reverse (Type 1c). This proposition raises the boundary issue of whether the SES typology could help us understand if cities or towns can address the sustainability problems they cause, or contribute to, outside of their local boundaries through excessive resource consumption and its related emissions. It is not possible to address this important issue here, but this point should be a priority in future refinement of the typology.

Second, inherent resource abundance is critical (Auty, 2001). Shortages of key provisions such as water can be mitigated only if social organization allows human actors to sustain effective collective action. Relevant responses could include modifying behaviors so that they are consistent with limitations imposed by the local environment, as well as adopting technologies that are sustainable over long periods. Type 1a cities may employ technology to overcome inadequate local resources, but Type 1c cities generally have no effective means to counter critical resource shortages. For example, affluent Persian Gulf countries can address water shortages with desalinization technology, but poorer arid countries generally do not have this option (Al-Mutaz, 1996), increasing vulnerability particularly in the short term.

Third, diversity in both social and biophysical systems is necessary for SESs to accommodate perturbations such as the loss of a crucial market or a catastrophic event. Multiplicity and redundancy, attained by investing in knowledge economies and having numerous commodity niches, promote the ability of settlements to adapt to new social circumstances as local and global conditions change.

Fourth, technologies, including infrastructure, must be accessible and function over long periods to distribute necessary resources, such as water and energy. Vital infrastructure must be efficient and redundancy must be resilient to exogenous events (Kassis, 2005; Coaffee, 2008). Settlement infrastructure, however, must be flexible enough, both socially and physically, so that sunk costs do not prevent rapid adaptation, a significant challenge in built environments. For example, the Brazilian city of Curitiba was able to quickly modify its urban transportation system in response to harmful commuter patterns (Rabinovitch, 1992).

Fifth, settlement management and effective governance is necessary. Settlements that plan and organize well, making good decisions regarding use and development of ecosystem services, are able to adapt. Such settlements make prudent collective decisions, balancing tradeoffs between growth and sustainability. Settlements with shared values and beliefs and equitable wealth distributions are better able to promote resilient practices (Folke et al. 2005; Alessa et al. 2007). Related to effective governance and management organization, reinforced and protected social values and networks enable settlements—particularly small-scale urban environments—to be more adaptable to external and internal shocks (Berkes et al. 2003; Alessa et al. 2008). Conversely, ineffective governance and management (i.e., resulting in gross inefficiencies and poor outcomes) can lead to settlements being less able to adjust to evolving social-ecological states that can cause significant stress.

The typology presented here is a first attempt to evolve the concept of neat SESs, or those with relatively clear system interactions, toward messy SESs. We believe that messy SES types will possess different dynamics of resilience and varying capacities to adapt to change, and ultimately require different approaches to management. In some SESs (e.g., Type 1c-3c), failure to develop adaptive strategies may mean acute morbidity and mortality, whereas in other SESs (e.g., Type 1a-3a) it may mean reduction in the range of goods and services. Researchers must address such differences carefully, since different rules and consequences will guide locally relevant management and adaptation strategies to avoid poor outcomes. Strategies adapted to address vulnerable settlements need to consider the specific circumstances that make such communities susceptible to untoward risks. An effective typology can provide a comprehensive means for researchers and stakeholders to evaluate settlement vulnerability and to subsequently develop appropriate strategies. That is, typologies useful in evaluating settlements based on the aggregate variables affecting resilience, and within a range that shows both aspects of vulnerability and resilience for various urban environments, may prove better in developing community-management and adaptation strategies than a neat SES. The variables that each indicator describes (Table 1 and 2) have potentially useful diagnostic value for understanding messy SESs. While Type A (resilient) and Type C (vulnerable) SESs represent the obvious diametric ends of the continuum, Type B (mixed or transitional) SESs are likely to be the most challenging as their combinations of indicators could prove particularly complex from a management perspective.

Conclusion

We have proposed that messy SESs need to be better refined to identify the most appropriate adaptive strategies for a given SES type. Nomadic and provisional settlements, such as refugee camps, have not been considered, but we have attempted to create a classificatory system that is applicable to most established habitation systems. Further refinement of this SES typology requires incorporation on a mass scale of the technologies upon which settlements rely. It also suggests a need for the engagement of diverse communities involved in understanding systems in general (e.g., physicists and biologists). The way a cell and a city function are remarkably similar. Both must selectively acquire and distribute resources to maintain specific functions such that the overall system operates continually and optimally. For example, a moderate degree of diversity is important in the functioning of SESs (Elmqvist et al. 2003), a concept comparable to the Law of Requisite Variety that there exists an optimal variety of actions available to a control system: too many and it becomes disorganized, too few and it becomes rigid (Ashby, 1956). Similarly, in cellular systems, the ability of the cytoskeletal array to reorganize quickly in response to stimuli (Alessa & Kropf, 1999) is comparable to the idea of flexibility in SESs (Walker et al. 2002).

In closing, we emphasize once again that our typology for SESs represents a continuum rather than a set of discrete categories. We recognize that larger settlements can display different aspects from the categories proposed. For example, Chicago has elements of resilient locales and also large areas that resemble transitional SESs. A simple tenet governs our species' life on earth: we seek the ability to acquire natural resources for material transformations that meet human needs and desires in sustainable ways. This quest has generated strategies that optimize adaptability and well-being. We believe that without a typology that better describes messy SESs, and ultimately more refined "best practices" for decision support systems and adaptive responses, meeting this goal will be difficult.

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COMMUNITY ESSAY

Identifying management needs for sustainable coral-reef ecosystems

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In 2007, I developed with the aid of the Earthwatch Institute and the Oak Foundation a capacity-building program in southern Belize to address issues of marine reserve management underpinned by science. The first component included group discussions on important issues related to the management of the reserves and review of scientific papers, strategic plans, and action plans. The second component included field research in the Sapodilla Cayes Marine Reserve and the Port Honduras Marine Reserve. The project's overall objectives and outcomes were to increase the participants' capacity to lead and educate regarding sustainable development and to promote networking among organizations that manage marine resources, enhancing their collective influence over policy decisions. From that program, the project group developed the concepts and management protocols for coral-reef sustainability elucidated below.

Introduction

Coral reefs are found predominantly between the Tropics of Capricorn and Cancer and provide homes for one-third of all marine fish species and many thousands of other species. The 6 million tons of fish caught annually in these waters provide an income for national and international fishing fleets as well as for local communities that rely on local fish stocks for sustenance. The reefs also act as barriers to wave action and storms by reducing the incident wave energy through reflection, dissipation, and shoaling, protecting the land and an estimated half a billion people that live within 100 kilometers of reefs. The coral-reef ecosystem forms part of a "seascape" that includes land-based ecosystems, such as mangroves, and ideally should provide a complete system for conservation and management (Mumby & Steneck, 2008).

Current challenges to coral-reef sustainability, that could destroy the world's reefs by the middle of the current century, include overfishing, destructive fishing practices, coral bleaching, ocean acidification, sea-level rise, algal blooms, agricultural runoff, coastal and resort development, marine pollution, increasing coral diseases, invasive species, hurricane/cyclone damage, and, in Indo-Pacific regions, crown-of-thorns starfish outbreaks. Against this backdrop of natural and anthropogenic insults, an important initial question is: How can management practices maintain sustainable coral-reef ecosystems? We now know that, while many reef organisms and fish have largely local dispersal, reef ecosystems have large-scale interconnections, for example with seagrass and mangrove ecosystems (Mora et al. 2006; Lo-Yat et al. 2006; Vollmer & Palumbi, 2007). This observation leads to a second question, namely how useful is the concept of single marine reserves over a global scale?

Linking Management Policy to Scientific Monitoring

An important environmental concept is that management needs to be evidence based. However, some managers might say that we do not need any more science on coral reefs–we know what the problems are, all we need is the resources to fix them. While that contention is true up to a point, it does not take into account the regime shifts that can occur at

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the ecosystem level where thresholds can all too easily be broken to produce an almost irreversible decline (Lyytimäki & Hildén, 2007).

An integrated approach that conjoins biological and social sciences to guide management decisions and influence policy is required. To take account of management-policy changes, feedback is needed via monitoring mechanisms (Dietz et al. 2003; Kajikawa, 2008; Pachauri, 2008). For coral reefs, such observation includes assessments of coral cover, coral species diversity, and fish and invertebrates, as well as physical and chemical parameters such as nutrients and salinity. These measurements indicate the effectiveness of management policies. In addition, regular and well-maintained scientific monitoring over time enables the development of a knowledge database of ecosystems that can be accessible to all stakeholders. Such a database can lead not only to knowledge-based management decisions in the short term, but ultimately to medium- and long-term management forecasting.

An Example: Global Monitoring of Coral Bleaching to Inform Management Regimes

Reef-building corals contain dinoflagellate symbiotic algae called zooxanthellae. The predominant source of nutrition for corals is in the form of photosynthetic products produced by the zooxanthellae. The symbiotic relationship between zooxanthellae and corals is that the zooxanthellae provide the coral with photosynthetic carbon, which is often enough to supply the coral's energy requirements, and in turn the coral provides protection and access to enough light for the zooxanthellae to photosynthesize. Coral bleaching is due to the loss of zooxanthellae by the coral. Most coral pigmentation is within the zooxanthellae, so when they are no longer present, the coral appears white, or bleached, because the calcium carbonate coral skeleton shows through the translucent living tissue. Bleaching occurs when the coral is exposed to prolonged above-normal temperatures that, together with increased solar irradiation, result in additional energy demands on the coral, depleted coral reserves, and reduced biomass (Lesser & Farrell, 2004). Hoegh-Guldberg and colleagues have estimated the frequency of future coral bleaching using projected sea-surface temperatures (SSTs) from four different general circulation models (GCMs) of the Intergovernmental Panel on Climate Change's (IPCC) IS92a emission scenario (Hoegh-Guldberg, 1999; Hoegh-Guldberg et al. 2007). These authors combine the SST projections with thermal thresholds for corals derived using the Integrated Global Ocean Services System (IGOSS) dataset[1] and from literature and Internet reports of bleaching events (bleaching tends to happen as a series of sudden "events" rather than as a gradual process). All SST projections indicate that the frequency of bleaching events is set to rise rapidly, with the highest estimates for Southeast Asia, the Caribbean Region, and the Great Barrier Reef and the lowest forecasts for the central Pacific Ocean (Hoegh-Guldberg, 1999; Hoegh-Guldberg et al. 2007). Some meteorologists predict that bleaching events will occur annually in most oceans by 2040 (see e.g., Hoegh-Guldberg et al. 2007). Southeast Asia and the Caribbean Region are projected to reach this point by 2020, triggered by seasonal changes in seawater temperature. El Niño events, themselves producing SST changes, would add to the problems.

To predict imminent rises in SSTs, the United States National Oceanic and Atmospheric Administration's Coral Reef Watch (NOAA CRW) develops and operationally produces satellite-based coral bleaching "nowcasts" and alerts that are available on the Internet (Liu et al. 2006). These products are based on nighttime-only Advanced Very High Resolution Radiometer (AVHRR) sea-surface temperatures from NOAA polar-orbiting satellites. This system, for example, provided notification of the 2005 Caribbean mass-bleaching event, indicating that average ocean temperatures in the area during July to October 2005 exceeded temperatures at any time during the past 154 years (NOAA, 2008). Corals grow within a very narrow temperature range, so that a few degrees of positive or negative variability will cause bleaching, and ultimately mortality, as happened in the Caribbean Region in 2005. Similar monitoring systems are in use for the Great Barrier Reef and, as with the NOAA system, such information provides invaluable help to marine reserve managers and other stakeholders of coral-reef ecosystems (Maynard et al. 2008).

Some Routes Toward Integrated Coastal Zone Management and the Development of Learning Outcomes for Sustainable Coral Reefs

Since the 1992 Rio Declaration on Environment and Development, emphasis on the transfer of technological knowledge and scientific understanding has encompassed four areas: legal and administrative, financial, technical, and human resources (Cicin-Sain & Knecht, 1998). While in exceptional cases devel-

[1] Data are compiled by a collaborative initiative undertaken by the World Meteorological Organization (WMO), the United Nations Educational, Scientific, and Cultural Organization (UNESCO), and the Joint Intergovernmental Oceanographic Commission's (JCOMM) Technical Commission for Oceanography and Marine Meteorology.

opment of Integrated Coastal Zone Management (ICZM) and ecosystem management has been achieved in the absence of government (Jorge, 1997), involving government-fisheries departments better facilitates policy development (Cernea, 1995; Tuler et al. 2002; Crabbe et al. 2009b).

ICZM is a complex worldwide governance issue requiring an integrated and coordinated approach. It involves many relevant stakeholders and policy initiatives need to be developed over long time scales. Ideally, marine ecosystems (i.e., corals and seagrass beds) should be closely linked to terrestrial ecosystems such as mangroves and coastal forests. In developing management policies, education and training to enhance human skills and institutional capacity in resource management is critical (Wescott, 2002; Balgos, 2005). Such instruction has engaged many communities with inherent and long-standing challenges to sustainability and has been carried out within the context of marine protected areas (MPAs) (Chircop, 1998; Crabbe, 2006), indigenous community-based conservation (Mutandwa & Gadzirayi, 2007; Tai, 2007), waste management (Agamuthu & Hansen, 2007), health (Tang et al. 2005; Raeburn et al. 2006), and disaster preparedness (Allen, 2006). Both developed and developing countries have used capacity-building programs (Eakin & Lemos, 2006; Kaplan et al. 2006; Rogers et al. 2007). While many, if not all, of these programs involve building competencies and empowerment in local communities, few of them involve policy makers or government officials (Mequanent & Taylor, 2007). Moreover, increased community capacity can potentially empower local communities to mitigate socioeconomic impacts of environmental change; however, evaluations of ICZM performance have revealed limited interest in furthering community development. Partnerships can be vital for ICZM, particularly where government policies link to local stakeholders (e.g., beach clean-up groups and marine wildlife associations) to produce collaborations that can involve people with vested interests in the coastal ecosystem (e.g., fishers, tour operators) and in ongoing management frameworks (Stojanovic & Barker, 2008).

The effective application of ICZM to coral-reef ecosystems entails the development of learning outcomes for sustainable coral reefs and stakeholders. These should address a number of themes, including:

1. The use of ecosystem and economic parameters to quantify the needs of marine reserves.
2. The development of tactics for leading, educating, and supporting issues regarding sustainable development of coral-reef ecosystems.
3. The incorporation of all relevant stakeholders into the formulation of policy issues pertaining to marine resource management-zoning plans.

Stakeholders can employ a number of methodologies to produce learning outcomes for management (May, 1993; Becker & Ostrom, 1995; McCance et al. 2007; Fletcher et al. 2008; Poteete & Ostrom, 2008). Box 1 identifies a set of twelve management needs derived from sustainability science that involve partnerships among government, nongovernmental or-

Box 1 Management needs derived from sustainability science.

1. Ecosystem zonation redesignated to balance stakeholders' wishes and evidence-based fisheries catches.
2. A community-based research program developed via participants. This should involve local fishers with qualitative and/or quantitative research methods.
3. Data of high accuracy. Quantitative ecosystem data needs to be verified statistically.
4. Comanagement plans between nongovernmental organizations (NGOs), communities, and fisheries departments developed to address problems of illegal fishers from states or countries outside the governance of the MPAs. This is a significant problem in reef areas close to more than one country or state.
5. Foster regular public meetings of stakeholders, as well as regular education events. Action plans need to be developed and monitored by staff and stakeholders alike.
6. Effectiveness of zoning monitored and quantified. This point relates to fishing practices, as well as to ecosystem health.
7. Encourage and maintain alternative livelihoods for fishers (e.g., in the tourist industry). Government agencies need to be involved in linking tourism and economic development.
8. Tourists monitored and sustainability encouraged. All stakeholders need to be involved, with penalties for unsustainable practices.
9. Effective management linked to the country's economy. Progress toward this objective is encouraged if fishing or another coral-related industry (e.g., tourism) is an important part of the country's gross domestic product (GDP). Politicians should be engaged at all steps in management discussions.
10. NGOs and marine protected areas (MPAs) link together. In areas where different NGOs are responsible for MPA management (e.g., in the MesoAmerican Barrier Reef), and where MPAs are distant from one another, it is helpful to link both NGOs and MPAs so that a greater area of reef can be managed.
11. Maintain regular information to all stakeholders, from the politicians to the local communities. Communication linked to the communities served (e.g. some oral, some printed, some via Internet) is important.
12. Management plans passed into law. The involvement of government officers (e.g., fisheries officers) as partners is key to this important outcome, which should ensure appropriate policing if resources are made available.

ganizations (NGOs), and communities to improve ICZM.

Sustainable Marine Reserves

Marine reserves are an important tool in the sustainable management of many coral reefs (Williams & Polunin, 2000; Cho, 2005). However, it is important that the reef ecosystems share regulatory guidelines, enforcement practices and resources, and conservation initiatives and management, underpinned by scientific research. An excellent example of an effective single marine reserve is the Great Barrier Reef in Australia operated and managed solely by the Great Barrier Reef Marine Park Authority (GBRMPA). In contrast, the second largest barrier reef in the world, the MesoAmerican Barrier Reef, is bounded by four countries (Mexico, Belize, Guatemala, and Honduras), each with its own laws and policies. Here, a number of single and separated marine reserves exist along the barrier reef. The authors of this essay have successfully transferred scientific expertise in Belize to local participants to generate scientific evidence to underpin future management and conservation decisions. Our scientific findings on the impact of hurricanes on reefs in Belize suggested that hurricanes and severe storms limited the recruitment and survival of nonbranching corals of the Mesoamerican barrier reef and advised marine park managers to assist coral recruitment in years where there are hurricanes or severe storms (Crabbe et al. 2008; 2009b; 2009c).

The MPAs need to share the guidelines, practices and resources mentioned above, justified by scientific research (see, e.g., Hills et al. 2006). Cooperative studies and networking across all levels improves capacity building and encourages innovative approaches to management, particularly across coral-reef, seagrass, and mangrove and forest ecosystems (Christie & White, 2007; Johnson & van Densen, 2007; Poulsen, 2007; Crabbe, 2009c).

This essay has addressed the two questions advanced in the introduction and has postulated a number of outcomes important for the sustainable management of coral-reef ecosystems. We and others (see, e.g., Mumby & Steneck, 2008) contend that the establishment of protected areas and policy development for sustainable conservation practices are key to sustainable ecosystems. Developing ICZM in the future will require both resources and iteration over many years to forge sustainable management processes and outcomes (McDuff, 2001; Wescott, 2002; Coffin, 2005; Mow et al. 2007). In cases where stakeholders have unresolvable differences, clear and disinterested leadership and a widely respected decision-making process are important to reduce the possibility that divergence does not deteriorate into conflict. The different backgrounds and imperatives of stakeholders are important in management negotiations, particularly if the model used is outcome-driven rather than process-oriented (Norris-Raynbird, 2004).

While climate change, through rising SSTs and coral bleaching, has the potential to destroy the majority of reefs by 2050, application of some, if not all, of the learning outcomes mentioned above will help in the resilience of the corals to anthropogenic and other insults. There are some examples of successful management, not least from the Caribbean Region, which has suffered overfishing and reef decline for many years. Several years ago, the Discovery Bay Marine Laboratory, working with the University of the West Indies, launched a number of initiatives (encompassing points 3-6 and point 9 from Box 1) on Dairy Bull Reef, on the north coast of Jamaica. This policy program resulted in a turnaround, leading to reef recovery (Idjadi et al. 2006). Most interestingly, following the Caribbean-wide bleaching event of 2005, live coral cover dropped to about 13% (from 46% in the previous year) and *Acropora* species branching coral to about 2% (from 33% in the previous year). Three years later, the coral cover at Dairy Bull Reef had increased to over 30% and *Acropora* species branching coral to over 20%.[2] This recovery to near-prebleaching levels suggests that application of ICZM can lead to reef resilience, even in the face of climate change. The further application of sustainability science and ICZM for coral reefs, in cooperation with grassroots organizations (Sobeck, 2008), will need enhancement from all stakeholders. As Gandhi said, “The world has enough for everybody’s need but not for anybody’s greed.”

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[2] It is apparent from our study that, despite the chronic and acute disturbances between 2002 and 2008, demographic data indicate good levels of coral resilience on the fringing reefs around Discovery Bay in Jamaica. The bleaching event of 2005 resulted in mass bleaching, but relatively low levels of mortality, unlike corals in the United States Virgin Islands where there was extensive mortality. Our work suggests that marine park managers may need to assist coral recruitment and settlement in years with severe acute disturbances, including hurricanes and bleaching events, by setting up coral nurseries and/or natural or artificial high rugosity substrate on the reef (Crabbe, 2009a).

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BOOK REVIEW PERSPECTIVES

John Polimeni, Kozo Mayumi, Mario Giampietro & Blake Alcott, *The Jevons Paradox and the Myth of Resource Efficiency Improvements*

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Our current global energy production and consumption patterns are unsustainable, whether one is concerned primarily about climate change, international security, or peak oil. Because today's economy and society are dependent on energy production and consumption, addressing our global energy issues will require a complex set of actions. We would be wise to draw on an understanding of the multi-scale synergies and feedback loops among global consumers, producers, and policy makers—as well as the roles of technology research and infrastructure investment—to inform these actions.

Many of us, however, would like to believe that there are easy answers. We environmentalists are often on the lookout for "win-win" opportunities where we can save energy (and therefore protect the environment) and also save money without worrying about broader systems behavior. *The Jevons Paradox and the Myth of Resource Efficiency Improvements*, by John Polineni, Kozo Mayumi, Mario Giampietro, & Blake Alcott, challenges the implicit assumptions behind our embrace of the win-win. The authors point out flaws in the expectation that, if we as individuals make decisions to conserve energy, a collective sustainability will automatically emerge.

The Jevons Paradox was first introduced by William Stanley Jevons in 1865. He developed the idea to describe a phenomenon in the growing coal sector. According to the Paradox, the invention of equipment requiring less coal consumption led to greater overall consumption of coal as the cheaper-to-operate equipment became valuable for many more uses. In other words, the "rebound effect" can, in some cases, actually be greater than one, rather than close to zero as suggested by some researchers. As Polineni and coauthors correctly point out, many of us have inconsistent reasoning regarding the systems implications of increased efficiency. We expect labor efficiency and productivity increases to further economic growth, leading to more jobs overall. However, we do not expect the economic growth stimulated by our localized energy efficiency to lead to increases in energy consumption overall.

The book explores in some detail how to navigate the various mechanisms by which the Jevons Paradox may or may not operate within complex adaptive multi-scale systems. Key is the potential disconnect between policies, designs, and decisions aimed at solving a current local problem (such as adding lanes to address highway congestion) and the tendencies of the larger system to adapt to the change and/or evolve over time (more uncongested lanes lead to more cars). The larger message for the systems analyst is to strive for integrated analysis across dimensions and scales; for the citizen, that sustainability requires a "willingness to change yourself in order to be able to co-evolve with other humans and the environment."

Chapter 1 is an introduction which poses that the global economy cannot grow infinitely in a resource-constrained world. It briefly lays out two societal options for addressing this situation. Option 1 is to look for alternate patterns of development no longer based on gross domestic product (GDP) maximization. Option 2 is to continue to assume that markets will self correct and find substitutes for scarce resources. These options do not sufficiently draw on the insight offered by Paul Hawken, Amory Lovins, & L. Hunter Lovins (1999) in *Natural Capitalism*: "For all their power and vitality, markets are only tools. They make a good servant but a bad master and a worse religion." Neither option explicitly focuses on the imperative raised by this book—leveraging the power of the market to address global energy and climate issues at sufficient scale.

Chapter 2 presents a history of the Jevons Paradox and related economic theory. This early observation of the Paradox constitutes one of the first recognitions of a rebound effect. The chapter stresses the difference between local, direct rebound and indirect, economy-wide rebound. The indirect effect is im-

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portant because money saved from energy efficiency is generally spent somewhere else, likely leading to additional energy consumption. There is a discussion of “backfire,” which is a rebound effect of more than 100%. To fully understand and to be able to quantify the rebound effect, it is important to quantify efficiency. The chapter correctly highlights confusion about the appropriate normalization factor for energy efficiency. Should we use physical units (tons of product or waste), monetary units (GDP), or welfare units (energy “services” in, say, person-kilometers)?

Chapter 3 shifts gears from the history of economic theory to complex systems and the challenges associated with bridging scales in analysis. The energy consumption per person or per unit of economic product may be the most straightforward way to assess energy efficiency. However, when economies reduce their energy consumption per unit of GDP, this is not necessarily ecologically meaningful. Global economy-wide total energy consumption is the ecologically meaningful measure. Returning to the micro-scale, the book discusses the evolution of and trends in automotive engine-energy efficiency (and corresponding trends in features—air conditioning, powerful engines—boosting overall energy consumption) since the 1940s. This chapter extends far beyond economics and energy efficiency, spending some time on the ambiguity of the north, south, east, or west orientation of the coast of Maine and the relationship and shifting causality between sizes of predator and prey populations. This broad discussion eventually feeds back into a more abstract focus on the interplay between efficiency and adaptation. The chapter returns to touch on efficiency as it relates to material standard of living and environmental loading, pointing out that the financial gains from local efficiencies may best be fed back into the larger-scale economy if the rebound effect of the Jevons Paradox is to be avoided. However, the policy-oriented reader anxious to avoid the Paradox yearns for a more detailed concrete examples.

Chapter 4 presents regression analyses of empirical national-scale energy intensity, GDP, population, and other data for the United States, Brazil, and several countries in Europe and Asia from 1960 to the present. These data suggest that the Jevons Paradox is present in these regions. The significance of these analyses could have been presented a bit more clearly, and the discussion could have more effectively built on previous chapters. For example, the multi-scale perspective so extensively discussed in Chapter 3 seems absent. It also would have been interesting to explore the relative magnitude of the effect of the Jevons Paradox in different countries or regions (such as a comparison of planned versus free-market economies) at different time periods (for example, during the 1970s energy crisis). As Joseph Tainter asks in his wonderful forward, “When does [the Jevons Paradox] not apply?”

Chapter 5 is a very brief conclusion that highlights the exponential nature of our current global economic and consumption trends. It emphasizes the importance of “reflexivity” in addressing our global energy situation, stressing that we cannot simply rely on our economic system to stimulate silver bullet technological innovation. After the authors had worked hard to convince readers that we should think through our energy situation carefully at multiple scales, it was a bit disappointing to see the absence of constructive, specific, thoughtful suggestions for global economic energy policy informed by study of the Jevons Paradox. Specifically, how can we develop synergies between local and global scales so that innovations in energy efficiency and/or energy decarbonization can be effectively scaled up?

The book focuses extensively on the interplay between the economic system and technology innovation. However, it is written exclusively from an economist’s perspective. Having one chapter from an engineer or technologist would have been a valuable addition. The technological component of any solution to our energy challenges must include more efficient energy use. The central point raised by the book is not that technological energy-efficiency innovations are counterproductive, but rather that relying on an unadjusted economic system to scale them up is.

The Jevons Paradox discusses an interesting array of issues from various perspectives relating to energy efficiency, technological innovation, and the behavior of economic systems. It describes at some length the difficulties of relating production and consumption at the local scale to broader globally desired outcomes. Though a strong case is made for energy policies informed by a sophisticated understanding of economic system dynamics, the authors offer limited guidance for moving forward.

Author’s Note

Although this article was reviewed by EPA and approved for publication, it may not necessarily reflect official Agency policy.

About the Author

Diana Bauer was one of the principal authors of EPA’s research strategy for sustainability. At EPA she has developed and managed the Collaborative Science and Technology Network for Sustainability (CNS), a research grant program, which supports regional projects using multidisciplinary science in sustainability-related decision making. She participates in government and academic societies developing research agendas for sustainability; green mate-

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In reading *The Jevons Paradox and the Myth of Resource Efficiency Improvements*, Box's maxim is usefully recalled early on: "all models are wrong, but some are useful." Box goes on to note, "not only does the selected model have to be pertinent in relation to the chosen narrative, but the selected narrative must also carry relevance for those using the results of the analysis."

The narrative of carbon-fueled economic growth was changed irrevocably with the formal and global acceptance of the phenomenon of climate change, as laid out in the findings of the Nobel Prize-winning International Panel on Climate Change. For centuries, largely because of its ability to perform against a nineteenth-century narrative, neoclassical economics, with its three enabling technologies of electrical power, the internal combustion engine, and modern communication systems for coordination and control, has been the preferred method for managing national economies. Neoclassical economics solidified nations' identities and dominance by documenting extraordinary production and growth of goods, but without registering either the free use of many natural resources and systems or unprecedented population growth.

Under this paradigm, today's developed world has achieved levels of sustained growth unrivaled even by the greatest past civilizations: Romans, Mayans, ancient Mesopotamia and Egypt, and some dynasties of China. However, the driving forces behind these latter civilizations were largely renewable biological systems (i.e., crops and people) with few dire long-term consequences. Today's economic growth and the current specter of climate change are both derived from common carbon-fuel sources, a fact commanding attention to all potential solutions, including the assumption that resource efficiency reduces consumption, which the Jevons Paradox reveals as a myth.

This book's new integrated exploration plays an important role in realigning an outdated narrative. William Stanley Jevons first formulated the paradox in 1865, arguing that "it is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth." The implication is that the focus on attaining efficient use of carbon fuel and petroleum-derived products will not sustain high levels of growth while curtailing consumption. Heightened technological adaptability without reduced resource consumption will not provide the carbon-fuel reduction necessary to diminish climate impacts.

Given the new narrative reality that the Jevons Paradox rests against, we should now consider it an important principle to be integrated into current economic analysis and policy formation. For example, in January, 2008 Tata Motors launched the Nano in India with a price tag of just US$2,500. A tiny four-seater, it is an efficient use of materials and promises mobility to thousands of Indian families with the expectation of hundreds of thousands more to follow throughout the developing world. The vehicle embodies the global trend of producing more for less and enhances the determination to manufacture millions. But, with its unprecedented resource efficiency in production, the Nano is not very fuel efficient. A perfect example of the Jevons Paradox, as noted in a long conversation on an Indian news website (Vail, 2008). Where else have resource efficiencies become paramount? A recent McKinsey report[1], a prime informant to the corporate community, shows Robert Socolow's wedge of efficiency providing more than enough expense reduction to afford technological improvements that reduce corporate carbon emissions.[2] Advice is available everywhere on reducing one's carbon footprint, mostly through efficiency measures (masquerading as reduction?). And, finally, there is talk among humanity's more daring of "going-off-grid" (i.e., becoming energy independent) (while remaining plugged-in).

All of this argues for a closer look at and change to the way we calculate gross domestic product (GDP), the prime national economic measure. If our calculation of GDP does not report the full effects of approaching peak oil by unmasking the chimera of technological efficiency, we will both fail to sustain a progressively equitable global economic system and

1 See Crets et al. (2007).

2 See, for example, Socolow et al. (2004).

falter in our own advance from a very favorable current position.

The authors, John Polemini, Kozo Mayumi, Mario Giampietro, & Blake Alcott, have made the book challenging to read and authoritative in their areas of expertise. Beginning and ending with jointly written chapters, the book layers history, complex adaptive systems, and empirical evidence in between.

The Jevons Paradox begins with a historical overview that constitutes just under half of the main text. The overview is thorough, yet fails to succinctly indicate missed opportunities where the lessons of the Jevons Paradox could have been integrated into mainstream economic theory. The authors thus puts us all at risk of continuing on a false path littered with arguing economists. As with most mature disciplines, changes often come incrementally, but conversely, watching recent financial markets create new instruments and algorithms to globally connect and communicate key variables, one wonders whether the field of energy economics might show a more aggressively inventive spirit.

Giampietro & Mayumi's section on complex adaptive systems is well presented and explained in ways that are accessible to readers unfamiliar with the discovery of quantum mechanics during the 1920s. Regrettably, the chapter fails to transform the fundaments of another discipline (i.e., economics), a phenomenon that has already occurred in similar attempts with linguistics, ecology, and psychology. Perhaps new operational platforms for organizing whole groups of data and connecting them in ways that transcend the notion of holons[3] and hierarchies will emerge to enable synthesis. In the chapter's conclusion, titled "Practical Lessons for the Analyst," two recommendations seem prudent: to attempt to change the narrative and using numbers to check quality and to apply integrated analysis across dimensions and scales. It may be much more difficult to achieve the remaining two propositions: to keep the observer in mind while completing the analysis and to remain motivated and convincing while engaging the caveat that any analytical outcomes are only approximate.

The use of examples from national economies animates Polimeni's section on empirical evidence. This chapter examines the United States, Europe, Asia, and Brazil. Simply put, "technological improvements may not be the universal remedy that policymakers have been counting on." The Jevons Paradox appears widespread, especially as illustrated in the case of Japan from 1971–2001. Over the long term, Japan's energy-efficient adaptations have led to a rise in energy consumption, even in this tightly controlled and closely managed country.

Who should read *The Jevons Paradox*? The book is most appropriate for those in the fields of economics and financial market analysis, engineering, ecological economics, materials and information sciences, and biotechnology. The book's insights are also highly relevant for people heading up business schools, departments of environmental and biological studies, and information-technology companies. In light of the many permutations of the Jevons Paradox, the book provides a route for entrepreneurs to take with abandon. Some general readers may find an interest, but to sustain it through the course of the book will take considerable persistent effort. It is not a light-hearted romp.

What next? The authors need to move their argument to multiple scales and to broaden it to include possible applications outside of carbon-fuel energy such as soil fertility, water use, and biological resource use and preservation. It would be instructive to address how genomics and nanotechnologies play into the equation. And the courses of developed and developing countries will take radically different roads in the very near future. As the writer on the Nano car noted, India may not have a middle-class like that of America or Germany, but it will have its own middle-class. This development implies increased overall consumption that will look very different from that of consumerist America. Finally, will increasing use and rapid growth of consumer electronics worldwide absorb the efficiencies at a fast pace, or not at all?

It would be intriguing and important to extend this concept for exploration by economists and market analysts, ecologists, engineers, software developers, and materials scientists at smaller scales than the nation. If GDP is to be redefined against the tidal wave of current global usage, then a new path will most likely come from the integrated efforts of non-state (open source) players. Even global financial markets can be drivers for change. These actors are now in the very active process of redefining themselves and the financial instruments that both mitigate risk and create fluid capital.

Author's Note

Statements and opinions expressed in articles, reviews and other materials herein are those of the authors; the editors and publishers. They do not necessarily reflect the opinions of the National Council for Science and the Environment or any employees or affiliates thereof.

[3] Coined by Arthur Koestler, a halon is something that is simultaneously a whole and a part.

About the Author

Kathryn Papp began her professional life in new product development in the private sector and for the past eighteen years has developed and launched programs and campaigns as disparate as: building a business constituency to support establishment of a new federal environmental research agency; initiating a research program integrating the ecology, economy, and human usage of three major transboundary watersheds; convening an expert panel to report to the Congressional Oceans Caucus on fisheries, energy, and marine diseases; and creating a national conference focused on gardens as a way to teach science and environmental studies for elementary teachers. Ms. Papp holds an MBA from the Thunderbird School of Global Management, and a bachelor's degree from the Honors College of the University of Toledo where she created a cross-disciplinary readings course in Asian studies. She reads extensively in the sciences, composes poetry, and enjoys music. A United States citizen and resident of Alexandria, Virgina, Ms. Papp's carbon footprint is 6.7 compared to an average of 27 for the country overall.

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Rejoinder from the authors

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First, heartfelt thanks to the journal for these reviews of our book. And also, of course, for the opportunity to respond to them—an intellectually fruitful arrangement that should be more widely applied. We even welcome responses to our responses to the reviews, if you will! The comments are appreciated and will help further our future research on the important and timely topic of the Jevons Paradox.

Diana Bauer, in our view, captures the Jevons Paradox accurately and concisely, including recognition of the problem of how to define energy efficiency's numerator, in some sense the social "product," with energy inputs in the denominator. She confirms as well our conviction that judging efficiency cannot be done without examining larger scales than particular products or economic sectors or even national economies—i.e., without extending the *system boundaries* under investigation. And the study of the Jevons Paradox, or "rebound," has led us to share Bauer's skepticism toward "win-win" technical solutions said to save the environment and save us money both! Bauer also mentions the irony that when *labor* instead of energy inputs is considered, analysts universally expect that productivity increases will increase employment, not "save" it.

We find Bauer's critiques largely accurate; indeed we debated most of them among ourselves while writing the book. First, it is true, as she says, that we do not provide "constructive, specific, thoughtful suggestions for global economic energy policy informed by study of the Jevons Paradox." In our view, a book whose goal is to explore the predicament associated with sustainability must contain at least three types of analysis: historical, theoretical and empirical. In our volume these appear in that order and we believe diagnosis must precede any prescriptions for a cure. The result of our critical (but hopefully not "destructive") analyses is thus not a general policy recommendation.

We thus agree with Bauer that "we cannot simply rely on our economic system to stimulate silver bullet technological innovation" or any one-size-fits-all solution. Energy policy should not repeat development theory's mistake of seeking a solution set valid for all countries. The energy security of a society depends on its ability to match two flows of useful energy: (i) that required by the society, which depends on its socioeconomic identity (population structure, level of services, diversity of activities outside the paid-work sector) and (ii) that supplied by the energy sector, which depends on that society's biophysical-technical identity (the mix of energy sources, technology and know-how, energy carriers, and end uses).

These two identities—of the socioeconomic system and of the energy sector—affect each other. At times the material standard of living has to be adjusted because of biophysical constraints (the identity of the energy sector affects the identity of the whole society), and at times technical innovations remove some of the biophysical restrictions. What is more, neither socioeconomic system nor energy sector are static over time but are "becoming," subjecting policy formulation to uncertainties bordering on genuine ignorance, especially regarding the goals of the socioeconomic system and the technical option space in, say, 25 years' time.

To return to Bauer's call for "global" policy suggestions, given international markets and free-rider problems perhaps such will be necessary—but because the energetic metabolism of societies changes, and there are many dozens of societies, even suggesting plausible overall solutions is extremely difficult. While the Kyoto path is promising, because it goes directly at the culprit, so to speak, how can global policies be formulated in light of diversity and uncertainty? Put another way, what flanking policies would be necessary for diverse societies to agree to Kyoto-like restrictions? Thus, indeed, perhaps our only "guidance for moving forward" is to recognize that, strictly regarding resource conservation and emissions reduction, the technological efficiency path deserves severe skepticism. Whether it is "counterproductive" or not depends on which goal is meant; energy innovations are useful for affluence and poverty reduction, but probably not for lowering energy-consumption rates. We welcome keeping both material-welfare and environmental goals in focus, but believe they are too often conflated.

We therefore see some ambiguity in Bauer's position that "the technological component of any solution to our energy challenges must include more efficient energy use." Likewise, when she writes that "the imperative raised by this book [is] leveraging the power of the market to address global energy and climate issues at sufficient scale" we are not sure whether she is suggesting global energy taxes. Of course, while the "market" usually reacts to higher energy prices with increased efficiency, the technological efficiency solution challenged by the Jevons Paradox explicitly does *not* assume higher (tax-induced) energy prices.

The charge that "having one chapter from an engineer or technologist would have been a valuable addition" to the book is debatable. In today's policy climate where the engineering, technical "silver bullet" approach of energy efficiency is praised by economists, prime ministers, and presidents, one feels: Stop, let us assume that efficiency increases are technically possible. So let us focus exclusively on the economic, society-wide, even anthropological or psychological question of what to do when we realize that a higher output-input ratio almost always means more output instead of less input. Concerning Bauer's call for "synergies between local and global scales," we are again unsure exactly what these would look like, and what the mix of private and government measures might be. But the Jevons Paradox at least draws attention to how small-scale changes affect large-scale results, a feature usually ignored in engineering approaches and universally ignored in evaluations of efficiency policy, where rebound is simply set at zero!

Concerning the book's regression analyses showing significant correlation between energy efficiency and energy consumption, we intended to start from a point different from the vast majority of, if not all, studies on the Jevons Paradox which have been on a micro-level. We do briefly summarize around twenty of these examples, relating their estimates of overall rebound based usually on microeconomic methodology. As with most general energy economics studies, we decided to use a simplifying macro-level model to obtain some understanding of the factors that cause the Paradox. Thus, it is true that this chapter was not able to relate the macro-level data and results to more local scales, and we welcome the suggestion that the results could in the future be correlated with different economic institutions, time periods prior to 1980, and perhaps energy prices.

Bauer wishes, moreover, that our chapter of statistical macro-level studies had been "built on previous chapters." If, however, the rebound literature shows us one thing, it is that while some "direct" rebounds have been reasonably accurately measured (if only for a single country), measurement of the environmentally relevant "total" or "economy-wide" rebound has been somewhere between elusive and impossible. But yes, the search for smaller-scale *explanations* of the Jevons Paradox, relating technology and consumption behavior, must go on.

To Kathryn Papp's suggestion that we broaden our study "to include possible applications outside of carbon-fuel energy such as soil fertility, water use, and biological resource use and preservation" we respond in the affirmative. A further example might be in space or regional planning: If space use for residences becomes more "efficient," for instance through building higher or denser, what are the consequences on the next wider scale? The answers could be somewhat different than for energy. We focused specifically on energy policy as a very timely area where technological efficiency is touted as *the* solution. To get into other areas would have given the book a more diffuse focus, whereas we had a very specific point, perfectly illustrated by the Jevons Energy Paradox. In addition, contributing to the energy debate with its intimate connections to other areas contributes by default to the discussion of other resources, including those that Papp mentions.

We agree with Papp's characterization of the dominant neoclassical paradigm as neglecting "the free use of many natural resources and systems or unprecedented population growth." Again, study of the Jevons Paradox is a start toward better understanding of the relations between the triad of resource prices, resource efficiency, and resource consumption. And some of us have specifically studied the effects on population growth of increased efficiency, particularly in agriculture. We also welcome Papp's mentioning that "advice is available everywhere on reducing one's carbon footprint, mostly through efficiency measures." Because many of these recommended measures involve consumer "sufficiency" and non-carbon-based energy sources, this point nicely opens up the policy discussion.

If Papp's example of the cheap, efficiently produced Nano automobile is invoked to show how its very cheapness should enable its sale to "hundreds of thousands more [people] throughout the developing world," this indeed demonstrates one of the main mechanisms for the Jevons Paradox—one moreover explicitly named by Jevons. She writes, correctly in our view, that "Socolow's wedge of efficiency provid[es] more than enough expense reduction" to finance "technological improvements that reduce corporate carbon emissions." However, assuming producer competition, this same efficiency provides the consumer with price reductions that increase the number of units sold; while the corporation may thus reduce emissions per unit, its overall emissions may rise. This is the general point of our systems analysis: The level or scale of corporate emissions has no *necessary* causal influence on the environmentally relevant society or world scale. We are, however, not sure of the status of her statement that "the Nano is not very fuel efficient." Again, how is efficiency here measured? And if this is true, the Jevons Paradox could not be tested on this example.

Papp's criticism that our pre-Jevons (1865) chapter "fails to succinctly indicate missed opportunities where the lessons of the Jevons Paradox could have been integrated into mainstream economic theory" is certainly true. This task, however, would have been not only beyond our present ability, but beyond the space available. One way to compensate for this deficiency is that, since neoclassical economics includes only capital and labor as "factors of production," it cannot address the efficiency problem pertaining to *natural* inputs. Furthermore, since the "backfire" of labor-productivity increases—increasing population and employment over several centuries—was seen as positive, perhaps both classical and neoclassical thinkers felt no need to investigate it. To be sure, classical economists from Ricardo and Sismondi and the Owenites and Luddites through Say and Mill to Marx hotly debated the question of whether greater production efficiency would throw millions out of work.

Thus, regarding labor inputs backfire is both uncontested and seen as good, while regarding energy inputs it is, from an environmental viewpoint, contested and perceived, correctly, as harmful. Jevons' main message seems to be that whenever *any* input is freed from former purposes, new purposes and/or new economic actors appear to employ the idle inputs. Were we to completely convert efficiency benefits into less production and consumption, rebound would indeed be zero. But the facts of poverty and human desire for comfort and prestige mean that, while, to prevent environmental catastrophe, input consumption *must not* rise, it in fact *does*. Therefore efficiency policy is not conservation policy.

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BOOK REVIEW PERSPECTIVES

Ted Nordhaus & Michael Shellenberger, *Break Through: From the Death of Environmentalism to the Politics of Responsibility*

Houghton Mifflin, 2007, 344pp, ISBN: 9780618658251

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Ted Nordhaus & Michael Shellenberger's new book, *Break Through: From the Death of Environmentalism to the Politics of Possibility*, continues the provocative debate that began with the publication of their original essay "The Death of Environmentalism: Global Warming Politics in a Post-Environmental World" in 2004. The book's central argument is that "we must no longer put concepts like nature or the environment at the center of our politics," and should focus instead on a more holistic approach where humans and human needs are considered part of the ecosystem as well as the creation of a new "politics of possibility." In this light, the authors offer scathing critiques of Environmental Justice, Not-in-My-Backyard (NIMBY) campaigns, the American environmental movement in general, the "pollution paradigm," and environmental hypocrisy (on this latter point the issue of Robert Kennedy, Jr. and his opposition to the Nantucket Sound wind park received an inordinate amount of attention). There is much to like in the book and much to question as well.

The call for a more holistic approach to environmental issues (i.e., *humans as part of the ecosystem and not separate*) is laudable and very much consistent with notions of sustainable development found increasingly in America's state and local governments and communities. Some social scientists argue that advocacy for sustainable communities in post-industrial America already has become one of the major social movements of our time (e.g., Kates et al. 2005). Widespread concern with the long-term carrying capacity of our conventional economic, social, and ecological processes and with the institutions required to manage them has led many states, communities, and citizens to pursue innovative sustainability policies. Early approaches to sustainability have placed rather differing emphases on these various needs (Pezzoli, 1997; Sachs, 1999), but in general the four core dimensions of sustainable communities include economic, social, institutional, and environmental considerations. In many respects, paradigm change is already evident and precedes Nordhaus & Shellenberger's call to action. Obviously, much more needs to be done, including the engagement of all American communities, not to mention the federal government, which hindered the sustainability movement during the George W. Bush Administration.

However, Nordhaus & Shellenberger argue that "sustainable development ignores the fact that ecological concern is a postmaterialist value that becomes widespread and strongly felt...only in post-scarcity societies." To support the argument, they provide a case study of Brazil and its inability to balance development needs with environmental responsibility. They also begin with the premise that "[t]he connection between affluence and the birth of environmentalism goes a long way toward explaining why environmentalism in the United States emerged in the 1960s and not in the 1930s." While an enormous body of social science research supports this premise, things are a bit more complicated, which has implications for their critique of what they call the pollution paradigm as well.

Public opinion research conducted by sociologist Riley Dunlap in twenty-four countries suggests that value change concerning the need for more rigorous environmental protection may be more global than anyone has suspected. While many citizens in post-industrial nations have expressed support for biocentric principles underlying environmentalism, as numerous scientific surveys document, people in developing nations have also accepted those environment-regarding principles. Surprisingly, Dunlap's survey indicated that a majority of respondents in *both* developing and postindustrial nations give a higher priority to protecting the environment than to the pursuit of economic growth (Dunlap et al. 1993). These findings are also evident in the *World Values Survey 2000* and in the Pew Research Center's 2007 47-Nation survey. However, when survey respondents were asked how much environmental problems may affect their own health and that of their immediate family, the residents of developing nations were

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highly likely to see *past and present danger* from environmental problems; in contrast, residents in industrialized countries were likely to express concern for environmental problems likely to surface *in the future* (defined in the survey as being within the next 25 years). These findings led Dunlap to suggest that "residents of the poorer nations—which often suffer from poor water quality and high levels of urban air pollution—are much more likely to see their health as being negatively affected by environmental problems at the present." Other surveys have echoed these findings regarding how objective conditions affect citizens' concern for environmental protection.

Certain cultural factors found among peoples in different world regions also have been identified as leading to increased environmental awareness, or at least increasing potential receptivity to sustainable development principles (Inglehart, 1995). Consequently, depending on the context, there are multiple paths to environmental consciousness and sustainable development besides postmaterialist value change, including, but not limited to, culture, religion, and objective environmental conditions such as polluted air and water, and the *effects* of climate change (e.g., temperature, drought, fire). Interestingly, the 2007 Pew survey found citizens in many developing countries (e.g., India, Nigeria, and Turkey) more concerned about global warming than residents of some advanced industrial countries (e.g., Germany, Great Britain, and the United States)! An international, inclusive, holistic, and effective sustainable development and natural resource-management paradigm should embrace a diversity of perspectives and experiences that go along with differing levels of development, environmental conditions, and cultural traditions.

Of course, just because public opinion indicates concern about the environment or climate change, or even suggests that citizens would prefer protecting the environment over some economic concerns as many international polls have found, does not mean that political and economic elites in developing and even advanced industrial nations have the same aims. While Nordhaus & Shellenberger focus on the problems and failures of the American environmental movement in dealing with climate change and other issues, I would suggest the focus should be more on the socioeconomic and political power structure in the United States and other countries that leads to inaction.

Given the difficulty ordinary citizens have in dealing with the complexities of environmental matters, and especially climate change, the processes by which societies confront complex and technical issues involving the broader public interest is important. The formation of environmental groups has been key in this respect. The environmental movement has been characterized as an eruption from "below" by many social scientists, with demands for increased citizen input in the decision-making process lying at their base. Environmental groups have pushed for increased democratization as a fundamental component of environmental policy. Political scientists have identified two distinct forms of political participation. The first form is the "elite-directed" mode of political action represented by sociopolitical institutions—as represented by political parties, bureaucrats, and industry—that are hierarchical in nature and mobilize action in a "top-down" fashion. In contrast, the second form is the "elite challenging" mode, a pattern of political activity that is generally more issue-specific, operates outside traditional political channels, and tends to use unconventional tactics to influence public policy. Environmental activism may be characterized as a form of elite-challenging activism in which the existing political and economic agenda is challenged and changes in policy sought. Obviously, if the public is skeptical and distrusts the movement, its effectiveness is compromised.

Nordhaus & Shellenberger report public-opinion data on the views of Americans regarding environmental activists as "extremists"; however, the overwhelming majority of opinion polls conducted in the United States since the 1990s paint a much more positive picture. While support for some indicators has declined in recent years, as Nordhaus & Shellenberger report, the overall view is still fairly positive. For example, a March 11–14, 2007 Gallup Poll found that 22% of the public agreed that the environmental movement has "definitely done more good than harm" and 44% agreed that the environmental movement had "probably done more good than harm." I would suggest that the environmental movement—which is enormously diverse in approaches and perspectives—continues to play an important role as watchdog(s) of political and economic elites and as a communicator of environmental information to citizens and the media. However, as Nordhaus & Shellenberger argue, the message needs to be more holistic, less dogmatic, and include human society. Ignoring economic and social considerations of natural resource management and environmental policy can lead to narrow and unrealistic policy prescriptions as well as a decline in environmentalist legitimacy.

My final thought here concerns the "politics of possibilities" and "dreaming differently" themes throughout the book. Given the nature, scale, and complexity of climate change, this is a noble and warranted call to action. However, the United States has some major barriers to developing and implementing a new type of politics. Many observers have argued that while the country shares many socioeconomic and political characteristics with other postindustrial democracies, such as those in the European Union, some very important differences lead to distinctly different approaches to policy making, as well as to policy stalemate—both domestically and internationally (or as political scientists say, "pluralist paralysis"). It has been argued that what most differentiates the United States from other postindustrial nations is a political culture that embraces individualism to a far greater extent, and also a governmental system that emphasizes separation of powers and federalism. Both these features of American politics have profound implications for how policy issues—such as climate change—are defined and managed. The American emphasis on self-interest and private property rights makes it very difficult to address communal problems such as climate change and resource degradation. An indication of this cultural orientation toward the sanctity of private property and belief in the virtues of limited government is manifest in the small size of the governmental sector relative to other postindustrial nations.

In contrast to individualism, communitarian, or organic political culture—much more evident in Western Europe and Canada—reflects a belief in the priority of community over individual rights in a number of important policy areas. These priorities reflect a commitment to public goods and the perception of a collective or common stake in the protection of the natural world. By contrast, individualism focuses on the rights of the individual, itself a cornerstone of capitalist democratic economic systems and classical liberal political thought. NIMBY and self-interested responses to policy issues are the result. This situation is exacerbated by American governmental arrangement, with specific checks and balances, as well as a federal system whereby the various levels of government—including the national, state, and local—are all involved in environmental affairs to varying degrees.

This set of institutions and cross-checks leads to an extraordinarily fragmented and complicated policy-making process. Failure to gain agreement among the many "players" involved in major public policy issues in the United States often leads to gridlock. Given our cultural and institutional barriers to change, I fear that we may be left with only our dreams for a positive national response to climate change. However, there has been movement among some state and local governments and communities to address this issue holistically. The development of an effective international regime will be even more difficult given the larger differences between nation states.

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Following an onslaught of climate change treatments in the popular and academic press alike, the majority of which follow a similar script, *Break Through* is a breath of fresh air. This is not to say Nordhaus & Shellenberger's thesis should be wholeheartedly embraced, for I take issue with several aspects, but the book makes insightful contributions to the dialogue on climate politics. Let us begin with a brief summary of highlights.

According to the authors, the nay-saying, limit-laden, doomsday politics of environmentalists, and the left more broadly, have failed. This approach to the global warming file in particular has contributed more to the problem than to the solution. Environmentalists' prescriptions for limits and individual sacrifice, and their lack of redemptive vision, do not inspire the creative social change desperately needed to address climate change. In short, environmentalists are long on problems and woefully short on solutions that, when offered at all, "*constrain* rather than *unleash* human activity" (emphasis in original). Much of this failure boils down to the persistent framing of global climate change as a pollution issue. But climate change is far more complex, requiring more imaginative solutions than regulating limits on carbon dioxide, a point, the authors argue, that major environmental groups have failed to grasp.

The authors urge, instead, a full-scale transition to a new energy economy, requiring that we unleash all the human creativity the current population has to offer. The best way to unleash ingenuity is by focusing on increasing prosperity. Prosperity brings out the best in people after all, and poverty and collapse (whether rhetorical or real) bring out the worst. Environmental concern, inherently a postmaterial politics, can only be fostered by first addressing material needs: "thinking ecologically depends on prospering economically."

Addressing material security is not simply a matter of raising living standards among the poorest of the poor, however. Ted Nordhaus & Michael Shellenberger point to the increase in the West of what they call insecure affluence: living standards that have not kept up with expectations, leading to increasing household debt at the same time that many types of income have become less secure. The lack of public concern for the environment, as well as the rise in xenophobia and other forms of intolerance, are attributed to insecure affluence. Attempts to generate commitment to climate change by fostering guilt, calling for constraint, and warning of ensuing doom, according to the authors, are not likely to be received warmly in such a social milieu. What we need instead is for environmentalism to function more like a church, capitalizing on the weak social ties that define the social capital of the new creative class, and moving away from issue-based politics to a values-based politics that embraces rather than challenges individualism and prosperity.

This work is not so much fresh as freshly-packaged, bringing together what have heretofore been unintegrated streams of argumentation, many of which, furthermore, have been restricted to academic literature. The authors provide hard-edged critiques of environmentalism, its essentialist ideological premises, and its political strategy, pointing out that environmentalists too often blame others for their failures. Noting a commonly cited environmentalist complaint, they state, "the problem is not that global warming is invisible; it's that environmentalists depend too much on the visible." The steadfast reliance on positivist notions of objective science as representative of the environment, combined with rhetoric about how Nature must be protected from humans, relies on the faulty belief that humans are separate from nature: "The issue is not whether humans *should* control Nature, for that is inevitable, but rather *how* humans should control natures—nonhuman and human." Assertions about speaking for Nature are ultimately authoritative and non-democratic claims to be above politics.

But, the authors argue, the belief that there exists a Nature separate from humans is no more tenable than the belief that there is a market separate from humans. By accepting that both are socially constructed, we raise the potential to (re)create both. This potential must inform the development of a coherent vision and ideological framework, currently lacking in the environmental movement. Environmentalists could look to churches, the authors suggest, for developing strategies to increase the breadth and depth of support, replacing the thin identity of environmentalism with a thick identity more akin to evangelicalism.

The authors also provide insightful and constructive critiques of contemporary environmental campaigns, including the Brazilian Amazon and the environmental justice movement. These two chapters, augmented by examples throughout the book, emphasize that political strategies: 1) must be deeply reflective of their political, economic, and cultural context; 2) must address root road blocks to prosperity (like poverty and debt); and 3) can only be effective when premised on building allies, not creating enemies.

My enthusiasm for *Break Through* is tempered, however, by several loose ends, contradictions, and ultimately a very dangerous premise. First, reference to academic treatments is selective, one might even say sporadic in places. The academic reader will thus find certain holes in the arguments posed, and can rightfully question the newness of much of Nordhaus & Shellenberger's social analysis. The complete absence of reference to the literature on environmental movements is particularly notable, considering the central focus of the book. But these absences in and of themselves are not sufficient to discredit the work. The authors, after all, are not academics, nor do they portray the book as such.

The work is also replete with glossed-over pragmatic issues that define the feasibility of the transition proposed. These include, for starters, the sheer magnitude of organizational and infrastructural changes that would be required to enable a shift to a new energy economy. Secondly, the authors appear to ignore the fact that the interests that have been so successful at opposing carbon limits are among the same that would (indeed do) oppose significant financial investments in alternative energy research, with the possible exception of carbon capture and storage for obvious reasons. Third, while the authors chide environmentalists for their failure to acknowledge the inevitability of climatic change and all its requisite social and ecological implications, they themselves fail to discuss this situation any further, notably the fact that the transition to a new energy economy would inevitably need to take place *in the context of* climate change calamity.

And now for the contradictions. The authors provide an astute critique of the essentialism that tends to emerge from both sides of the environmental political divide, noting that "there is no single spirit or essence that defines us. Humans are not essentially opportunistic, reactive, conservative, creative, or destructive." And yet the authors' central thesis is premised on an unquestioned conclusion that empirically has very mixed support, that prosperity brings out the best in people (and environmental concern in particular), while poverty and collapse bring out the worst (and a lack of environmental concern in particular). This is certainly a deterministic and arguably essentialist statement, for which there is a multitude of counterevidence. While the social consequences of crisis is an important area of social scientific research, we are far from the point at which we can draw generalizable conclusions, and such conclusions, if and when they emerge, are highly unlikely to be universal. The same, of course, can be said of the environmental salience/prosperity relationship.

Contradiction number two: the authors largely suggest a politics that accommodates consumerism, rather than replaces it: "The problem is that none of us, whether we are wealthy environmental leaders or average Americans, are willing to significantly sacrifice our standard of living." True enough, but rather than serving as a justification for challenging Western predispositions for lavish material consumption, the authors suggest that we need to simply find new energy sources to support current Western living standards (which they admit are ever-rising on the material scale), while at the same time raising global standards to similar levels. One might ask, if we were not able to accomplish this remarkable feat with fossil fuels, how is it possible that we would be able to do so with far less accessible renewable energy sources? At one point, the reader is asked: "Is it really so hard to imagine a world with healthy forests, a stable climate, and seven to ten billion people living in sustainable cities?" Um, the answer from this reader is, yes.

How is it that these authors do not find this vision problematic? Because by doing away with political discussion of ecological limits, we somehow do away with the limits themselves. Their insistence that "[t]here are still seven billion wondrous animals, each one of us capable of making ourselves into something utterly unique" (but not apparently also capable of leaving an ecological footprint of any consequence) is pure Julian Simon 27 years later. Nordhaus & Shellenberger thus embark on a path that has been trodden repeatedly, one that has not taken us any further down the road toward environmental improvement.

The authors' call for a more constructive politics that addresses prosperity and inspires creativity should most certainly be heeded. But a politics that ignores ecological thresholds is as dangerous as a politics that ignores human ingenuity is ineffective. Rather than embrace environmentalism as a solely postmaterialist value, environmentalists would benefit from recognizing the many ways, places, and forms in which environmental concerns are in a sense no longer postmaterial at all. What environmental degradation represents is not solely threats to recreational opportunity and old growth forests, but to security of home and family, the very personal security concerns that the authors describe as so definitive of Western social context today.

I certainly do not recommend dismissal of this work, but neither do I suggest fully embracing it. It is a good read that must be taken with the proverbial grain of salt. As the authors note, we need a politics "powerful enough to transform the global energy economy," and for this enterprise, all contributions are welcome.

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Is the way we are living now sustainable? Do Ted Nordhaus & Michael Shellenberger provide an effective vision to move us toward sustainability? The answer to both questions is probably "no."

The authors argue that because of its focus on pollution, the environmental movement has brought us about as far as it can. To solve the really knotty problems presented by global warming will require a new way of looking at environmental issues. They argue that we will not be able to work our way out of this problem with regulatory schemes alone. Rather, we will need to harness the power of investment:

> [O]vercoming global warming demands something qualitatively different from limiting our contamination of nature. It demands unleashing human power, creating a new economy, and remaking nature as we prepare for the future. And to accomplish all of that, the right models come not from raw sewage, acid rain, or the ozone hole but instead from the very thing environmentalists have long imagined to be the driver of pollution in the first place: economic development…[What is needed is] an investment-centered approach…[The problem] must be understood more as a national economic development agenda than as a regulatory framework to limit carbon emissions…What environmental leaders have so far refused to do is put this vision of human power, growth, and development at the center of their politics.

The authors believe we need to harness the power of investment because of four factors that environmentalists have largely ignored. First, the success of pollution-control regulation in the latter half of the twentieth century shapes the way we see environmental problems and limits the ways we can imagine to deal with them. Second, "environmental issues are not as high a priority as prosperity is." Third, people will not turn their attention to environmental issues until their safety and security needs are met, until they feel securely affluent. Although Americans are wealthy by the standards of the rest of the world, their commitment to environmental values is shallow because of increased economic and social insecurity marked by desire for status and belonging and "the gradual return to…survival values, such as xenophobia, patriarchy, and the acceptance of violence…what we are describing…as insecure affluence." Finally, the rest of the world will not respond to global warming unless they can develop; "indeed, around the world there is a very strong association between prosperity and environmental values."

Is the way we live now sustainable? The authors say it is not. We do not need to look far to find others who share that view. In a recent keynote speech at the BookExpo America conference, Thomas Friedman (2008) pointed out the consequences of adding one billion people to the population of earth, which the United Nations projects will happen in the next twelve years. Friedman said if we give each new person a 60-watt incandescent light bulb and those billion people turn on their bulbs for only four hours per day we would need to build the equivalent of about twenty coal-burning power plants.

Do Nordhaus & Shellenberger offer a vision to move us forward? They suggest "a new social contract appropriate for our post-industrial economy." Although Friedman (2008) says that America is not ready to meet that challenge, Fiorino (2006) observes that we have already made great strides in describing what this "contract" might look like. "The key question [now] is this: How do we design and build a regulatory system that will promote a continuing, broad, and enduring greening of industry that builds on the demonstrated achievement of the leading firms?" Analysts have pondered this question for many years. For example, Fiorino suggests the Lee Thomas and William Reilly approach that looks forward to a new paradigm, including: "(1) defining the environmental 'problem' as more than just pollution control; (2) expanding the use of consensus-based processes; (3) developing new policy tools to complement regulation; and (4) working to integrate across environmental media and policy sectors, such as agriculture and energy." Nordhaus & Shellenberger have a deep connection to the environmental movement, but the argument presented in this book is—by now—fairly conventional and their prescription notably vague.

Their work finds an echo in Cohen (2006) and Fiorino (2006), who each trace the history of environmental protection in the United States along similar paths of first regulation, then regulatory reform, and now sustainability. With Nordhaus & Shellenberger, both Cohen and Fiorino recognize that "the old regulation has unwanted side effects and is unsuited to the task of protecting the environment in a rapidly changing world" (Fiorino, 2006). Nordhaus & Shellenberger argue that because of the "intersection of prosperity and ecological concern…[we] must create the conditions for prosperity in the developing world." They describe the new social contract to accomplish this:

> The new vision of prosperity will not be the vision of economic growth held by those who worship at the altar of the market. It will define wealth not in gross economic terms but as overall well-being. Wealth will be defined as that which provides us with the freedom to become unique individuals. It will embrace our power to create new markets. And it will turn the environmental movement's conditional support for economic development on its head: developing economies will be sustainable precisely to

> the extent that we invest in their development.

In contrast with Nordhaus & Shellenberger, both Fiorino and Cohen present more concrete prescriptions. Before the United States can effectively support sustainability abroad, Fiorino outlines five important steps: change the laws to promote regulatory and business innovation; focus implementation on "the better, proven environmental performers" by offering them more flexibility; offer "environmental management contracts" based on core performance indicators (i.e., emphasize performance over process whenever possible); replace the deterrence model of regulation with a facilitative approach for small operations; and establish performance agreements with industry organizations.

Cohen (2006) envisions six steps the United States should take. These might be summarized as investments; improved information about environmental conditions; better communication and understanding of environmental data; improved education of environmental professionals; better economic policies that lead to sustainable development; advanced environmental analysis and pollution prevention; and expanded community-based institutions to implement sustainable strategies. Although they do not say so, these kinds of investments might typify what Nordhaus & Shellenberger have in mind as steps the United States could take to promote prosperity at home and abroad.

People raising the alarm about climate change say we need to move quickly with whatever strategy we choose. Friedman suggests that we reached a tipping point in about 2000, after which five big trends began to work together to conspire against solving the problem. These trends are energy and resource supply and demand, petrodictatorship, energy poverty, biodiversity loss, and climate change. Friedman (2008) sees no easy way out and remarks, "Americans cannot buy enough compact florescent bulbs and hybrid vehicles to reverse the trends."

Fiorino (2006) observes that partisan disputes held the United States back during the latter part of the twentieth century. For those who agree that something must be done about climate change, the disputes were based on different behavioral assumptions about how policy tools actually work. Schneider & Ingram (1990) describe the suite of possible policy solutions. Each is based on a set of beliefs about how people actually behave in the face of a problem. They suggest five general policy alternatives: authority, incentives, capacity building, symbolic and hortatory, and learning. From my reading of Nordhaus & Shellenberger, Fiorino, and Cohen I would say they all favor a prescription that retains authority, incorporates incentives, and invests in capacity building. In other words, they all recommend what Fiorino called a "mixed-scanning" approach (see also Etzioni, 1986). Leaders can help the process along by exhortation and choosing the right symbols to frame the debate.

Is that mixed approach going to be enough? In the Introduction to their book of readings entitled *The State and Nature,* Clarke & Cortner (2002) observe that

> [O]ver the space of two hundred years there has been a marked increase in the voices heard in the environmental policy arena. With the introduction of new voices there comes a different conception of nature, or at least different beliefs of what is important and what is not. And, while the extension of democracy in this manner is generally considered a positive development, it is possible to have too much group identification and not enough community spirit. We believe that this is the political condition facing the United States in the twenty-first century…What many people think is needed at this juncture is a political movement, and strong leadership to break what scholar James MacGregor Burns called in 1963 the "deadlock of democracy."

An investment agenda might be part of such a political movement. A recent article in *The New York Times* gives us a window on how this might work using the example of human garbage. A combination of regulation, incentives, and investments has made it possible to safely incinerate trash in much of Europe. But the problem is huge. Despite being a hot issue, success in coping with trash depends on "the structure of government, management expertise, and national priorities" (Rosenthal, 2008). That assessment, from a spokeswoman for the European Commission's Environment Directorate, sounds a lot like Nordaus & Shellenberger, among others, who recommend that we need to take a new look at the toolkit for sustainability.

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