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EDITORIAL

Maurie J. Cohen
Editor

The roots of sustainability science: a tribute to Gilbert F. White

While the intellectual shoots of sustainability science are tangled and diverse, one of the most important taproots surely springs from the pioneering work of geographer Gilbert F. White who passed away in October, 2006 at his Colorado home at the age of 94. From our present-day vantage point, it is difficult to fully grasp his prescience because the once-radical views he proffered regarding nonstructural adaptation to hazards are now considered unexceptional in most quarters. This awareness, unfortunately, has not been easily translated into action. In many parts of the world, ineffectual policies and individual impertinence have stymied change and the number of people living in harm's way has continued to spiral upward. White devoted his life to trying to break us of our habituated practices and their tragic consequences.

Through teaching, writing, public service, and charitable undertakings, White began as early as the 1930s to challenge deep-seated ideas regarding human control of the natural environment. One of his most important insights, formalized in his 1942 doctoral dissertation, *Human Adjustment to Floods*, questioned the warrant of large-scale water diversion projects. Such an allegation was heretical, even misanthropic, at the time. After all, in the United States and elsewhere, massive land transformation programs were being implemented. The Tennessee Valley Authority, the Army Corps of Engineers, and the Bureau of Reclamation were ascendant and thousands of wide-eyed visitors came to tour the imposing facilities built under the aegis of these public bodies. This was a period of major levee construction along the Mississippi River and colossal dam development in the western states. White drew attention to the shortsightedness and ultimate futility of these efforts and simultaneously cultivated a wisdom that today buttresses key tenets of sustainability—the obligation of current generations to the future, the need to adapt ourselves to the limits of biophysical systems, and the quest for right livelihood.

An important thread in White's proto-sustainability research was how societies adapt to uncertainty generated by the changing frequency and scope of hazards such as flooding, drought, land degradation, and climate variability (see, in particular, Burton et al. 1993). Together with colleagues, he studied resilience to vulnerability and this work gave rise to a prominent school of risk analysis that has spread far beyond its original field of geography and infiltrated a diverse array of domains, including the sociology of risk (Cohen, 1996; Renn et al. 2001), decision sciences (Kleindorfer et al. 1993; Pigeon et al. 2003), environmental assessment (Flynn et al. 2001; Farrell & Jäger, 2006), and development studies (Pelling, 2003; Bankoff et al. 2004).[1]

For all of its discomfiting potency, White's original work on hazards represented an extension of claims advanced nearly a century before by George Perkins Marsh, the Vermont-born diplomat and polymath who meticulously documented the profound and unremitting effects of human enterprise on the landscape (Lowenthal, 2000). However, technology through the end of the nineteenth century remained comparatively rudimentary and modifications consisted principally of agricultural conversion, logging, and mineral extraction. During the years following World War I, industrial production became far more directed, dynamic, and capable. At its core were fossil fuels and novel modes of applied science that, when yoked together, allowed for the fundamental reengineering of entire regions.

In the United States, behemoth earthmoving machines reconfigured the physical geography of whole river basins that once suitably reshaped, were further transformed by ambitious development schemes organized around natural-resource appropriation and energy production. White spent most of his life chairing countless taskforces—several of them under White House or Congressional auspices—to mitigate the flood damage caused by these ill-advised and

[1] Although White himself was not a member of the faculty, the Graduate School of Geography at Clark University provided an especially fertile institutional setting for these multifaceted and interdisciplinary endeavors during the 1970s and 1980s.

seemingly inexorable pursuits. He began gravitating toward this vocation while working as a staff secretary for the Natural Resources Planning Board, a federal agency that served as a laboratory for innovative New Deal regional planning. After being interned in Baden-Baden during World War II, White was appointed president of Haverford College (at the age of 35) and held this position for a decade until he became chair of the Department of Geography at the University of Chicago. During this period he concurrently served as president of the American Friends Service Committee (AFSC) and led numerous study teams investigating water management in Africa, Southeast Asia, and elsewhere around the world.[2]

Perhaps more than anyone else, White nurtured many of the principles that would eventually give rise to the contemporary concept of sustainable development. For example, in 1952 he delivered a series of speeches calling upon affluent industrialized countries to help developing nations formulate conservation strategies that could foster economic development. As a Quaker, and in conjunction with AFSC, White maintained an indefatigable interest in voluntary service and domestic and foreign humanitarian assistance. His activities in this realm during the 1950s resulted in a series of AFSC assistance programs that eventually became the template for the Peace Corps.[3]

White carried these ideas forward into the global arena through his work forging international scientific alliances designed to focus public attention on a growing array of global environmental problems (including the threat of nuclear war). He became involved with the Scientific Committee on Problems of the Environment (SCOPE) during the late 1960s and served as president of the group during the critical years following the 1972 United Nations Conference on the Human Environment in Stockholm. As a result of his vaunted position and personal capacity to mobilize scientific expertise, White came to play an important role in the development of the United Nations Environment Program and several allied institutions.[4]

His academic pursuits epitomized the schizophrenia inherent in geography and he resided throughout his life in the precarious netherworld between the natural and social sciences. Neither geologist nor sociologist, his work did not fit into conventional categories and orthodox scholars were perpetually suspicious about his disciplinary loyalties. To add further complication, White practiced a highly pragmatic and applied mode of research that was never fully embraced by the more cloistered standard-bearers in the field.[5] Rather than analytic rigor or theoretical elegance, he devoted himself to expanding the range of human choice and this commitment prompted some of his more truculent critics to chide him for being a social engineer and for consorting with the political establishment. Though similar criticism persists today, White's balance of academic inquiry, public service, and participatory action provides sustainability scientists with a valuable model of how to effectively integrate intellectual activity with worldly engagement. A consortium led by his former student Robert Kates succinctly captured this commitment a few years ago, writing that "[i]n areas like climate change, scientific exploration and practical application must occur simultaneously. They tend to influence and become entangled with each other" (Kates et al. 2001).

White's ability to navigate successfully between the realms of science and politics was at least partly attributable to his sanguine understanding of the relationship between scientific expertise and policy making. The real challenge for him involved getting relevant research into the hands of resource managers and their political overseers. This resolve was perhaps most visibly demonstrated upon his relocating to the University of Colorado where he founded the National Hazards Research and Applications Information Center (now the Natural Hazards Center). Since its 1974 inception, the Center has sought to bridge gaps separating scientific investigation, policy formulation, and tangible action. The Center's annual summer retreats provide collaborative forums for researchers, policymakers, and practitioners involved in hazard mitigation and disaster preparedness, while its bimonthly report, *Natural Hazards Observer*, offers a straightforward digest of news and professional information. Steadfast dedication to this brand of managerialism served White well during most of his career.[6]

[2] For a comprehensive review of White's lifetime achievements, Robert Hinshaw's (2006) biography is an indispensable resource.

[3] Hinshaw (2006) recounts an invitation that White received from Sargent Shriver, the founding director of the Peace Corps, to return to Washington to serve as his assistant. White turned down the opportunity because he had only recently taken up his position at the University of Chicago.

[4] More recent initiatives such as the International Human Dimensions Program on Global Environmental Change, an outgrowth of SCOPE, are consistent with White's vision of combining scientific inquiry, interdisciplinary investigation, and global collaboration.

[5] The historical basis of White's intellection orientation, as well as the utility of his pragmatism, has been the focus of considerable discussion. See, in particular, Kates (1987), Wescoat (1992), Sunley (1996), Proctor (1998), Staeheli & Mitchell (2005), and Hobson (2006).

[6] Hinshaw (2006) relates an anecdote where White, soon after launching the Center, informed his newly-hired assistant that she would likely need to find another job in two or three years. He

It is probably fair to say that White's activities during the latter decades of his life—specifically his chairmanship of the Nevada State Technical Review Committee on Socio-Economic Effects of Nuclear Waste Disposal from 1986 until 1993—strenuously tested this propitious view of science in the service of technical decision making. A sadly ironic consequence of his long life is that White lived to witness the pitiful government response to Hurricane Katrina in 2005 and the political fallout generated by such tragic malfeasance. There may be, though, some recompense in the fact that with New Orleans swamped by several putrid feet of water and the Gulf Coast a shambles few knowledgeable observers had the temerity to refer to the catastrophe as a "natural" disaster.

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References

Bankoff, G., G. Frerks, & D. Hilhorst (Eds.). 2004. *Mapping Vulnerability: Disasters, Development, and People*. London: Earthscan.

Burton, I., Kates, R., & White, G. 1993 [1978]. *The Environment as Hazard,* 2nd ed. New York: Guilford Press.

Cohen, M. (Ed.). 1996. *Risk in the Modern Age: Social Theory, Science, and Environmental Decision-Making.* New York: Macmillan.

Farrell, A. & J. Jäger (Eds.). 2006. *Assessments of Regional and Global Environmental Risks: Designing Processes for Effective Use of Science in Decisionmaking*. Washington, DC: Resources for the Future.

Flynn, J., P. Slovic, & H. Kunreuther (Eds.). 2001. *Risk, Media, and Stigma: Understanding Public Challenges to Modern Science and Technology*. London: Earthscan.

Hinshaw, R. 2006. *Living With Nature's Extremes: The Life of Gilbert Fowler White*. Boulder: Johnson Books.

Hobson, K. 2006. Environmental responsibility and the possibilities of pragmatist-oriented research. *Social and Cultural Geography* 7(2):283-298.

Kates, R. 1987. The human environment: the road not taken, the road still beckoning. *Annals of the Association of American Geographers* 77(4):525-534.

Kates, R., Clark, W., Corell, R., Hall, J., Jaeger, C., Lowe, I., McCarthy, J., Schellnhuber, H., Bolin, B., Dickson, N., Faucheux, S., Gallopin, G., Grubler, A., Huntley, B., Jager, J., Jodha, N., Kasperson, R., Mabogunje, A., Matson, P., & Mooney, H. 2001. Sustainability science. *Science* 292(5517): 641-642.

Kleindorfer, P., Kunreuther, H., & Shoemaker, P. 1993. *Decision Sciences: An Integrative Perspective*. New York: Cambridge University Press.

Lowenthal, D. 2000 [1958]. *George Perkins Marsh: Prophet of Conservatio*n, 2nd ed. Seattle: University of Washington Press.

Pelling, M. (Ed.). 2003. *Natural Disasters and Development in a Globalizing World*. New York: Routledge.

Pidgeon, N., R. Kasperson, & P. Slovic (Ed.). 2003. *The Social Amplification of Risk*. New York: Cambridge University Press.

Proctor, J. 1998. The social construction of nature: relativist accusations, pragmatist and critical realist responses. *Annals of the Association of American Geographers* 88(3):352-376.

Renn, O., E. Rosa, T. Webler, & C. Jaeger (Eds.). 2001. *Risk, Uncertainty, and Rational Action*. London: Earthscan.

Staehili, L. & Mitchell, D. 2005. The complex politics of relevance in geography. *Annals of the Association of American Geographers* 95(2):357-372.

Sunley, P. 1996. Context in economic geography: the relevance of pragmatism. *Progress in Human Geography* 20(3):338-355.

Wescoat, J. 1992. Common themes in the work of Gilbert White and John Dewey: a pragmatic appraisal. *Annals of the Association of American Geographers* 82(4):587-607.

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apparently believed that the task of disseminating expert knowledge to hazard managers could be completed during this relatively short timeframe and the Center would then be able to close its doors.

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ARTICLE

Growing interest in carbon capture and storage (CCS) for climate change mitigation

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Interest in technologies associated with carbon capture and storage (CCS) has been growing rapidly in both the public and private sectors over the past five to ten years as governments, industry, and individuals grapple with how to reconcile increased energy demand with the need to reduce atmospheric carbon dioxide (CO_2) concentrations to mitigate the risks of climate change. CCS technology involves capturing the CO_2 produced during fossil-fuel combustion and storing it in underground geologic reservoirs instead of emitting it into the atmosphere. The idea of engineering the storage of carbon has developed from relative obscurity to an increasingly recognized approach to stabilizing atmospheric CO_2 concentrations. This paper (1) identifies several influential nongovernmental stakeholders and discusses their contributions to CCS and (2) describes how governmental influence through political positions, government-supported research and development, and economic policy tools and international treaties have influenced CCS initiatives. While the relative strength of nongovernmental and governmental influences is not quantified, this treatment of the various factors contributing to the advancement of CCS technology highlights the complexity associated with integrating developments in science and engineering into sustainable practices.

KEYWORDS*:* Climatic change, carbon cycle, energy consumption, socioeconomic aspects, fuel technology, Kyoto Protocol, political attitudes, policy reform

Introduction

As the current impacts and future risks of climate change become more apparent, and the atmospheric concentration of carbon dioxide (CO_2) continues to increase, carbon capture and storage (CCS) technologies provide a potentially valuable set of tools for achieving the magnitude of emissions reductions required for CO_2 stabilization as society gradually transitions to a non-fossil fuel energy system. Interest in CCS technologies has been growing rapidly in both the public and private sectors over the past five to ten years as governments, industry, and individuals grapple with reconciling increased energy demand with the need to reduce atmospheric CO_2 concentrations to mitigate climate change.

The concept of engineering systems to deliberately capture CO_2 to store the associated carbon in a reservoir other than the atmosphere has evolved from relative obscurity two decades ago to an increasingly recognized set of potential climate change mitigation options. This paper identifies several influential nongovernmental stakeholders and governmental influences that have advanced CCS. I begin by briefly reviewing the technologies associated with CCS that involve geologic CO_2 storage and provide background on other carbon-storage options, including terrestrial carbon sequestration and oceanic carbon storage. I then describe the influence of several specific nongovernmental stakeholders involved with advancing CCS and highlight governmental influence through political positions, government-supported research and development (R&D), and economic policy tools and international treaties. Finally, I discuss the complexity of the nongovernmental and governmental influences on CCS development and relate these to the social challenges of integrating science and engineering developments into sustainable practices.

Carbon Capture and Storage in Context

While this paper focuses on CCS to capture the CO_2 produced during fossil-fuel combustion and to store it in underground geologic reservoirs, the advancement of the relevant technologies is intricately linked to the development of other carbon-storage options, including terrestrial carbon sequestration and oceanic carbon storage. Terrestrial carbon sequestration refers to the storage of carbon in the biosphere relying on the photosynthetic process of capturing and converting atmospheric CO_2 into organic carbon. The notion of ocean storage generally applies to the direct injection of captured CO_2 into the oceans, but also can include other mechanisms for enhancing oceanic uptake of carbon. Another potential carbon-storage approach, often referred to as mineral carbonation, involves chemical reactions that transform the carbon in gas-phase CO_2 into solid-phase carbonate minerals.

As the value of storing carbon in a reservoir other than the atmosphere has become more widely recognized, interest in all of these options has been increasing. Among these approaches, terrestrial carbon sequestration involves the least engineering and the co-benefits of enhancing biomass growth are attractive. Although enhanced biological storage of carbon has the potential to reduce atmospheric CO_2 considerably (Winjum et al. 1992; Mutuo et al. 2005), recent research suggests the biosphere may soon become a net source rather than a net sink of atmospheric carbon due to changes in climate (Lenton & Huntingford, 2003). In addition, ecologically precarious monoculture plantations and the replacement of native forests with faster growing species could negate improvements from large-scale biological storage (Kueppers et al. 2004). This general approach also has the potential to decrease stream flow and to increase soil salinization and acidification resulting from afforestation (Jackson et al. 2005). Terrestrial carbon sequestration is the carbon-storage approach that appears to be the most acceptable option to the general public, as the idea of planting trees as a way to mitigate climate change has been proposed by many prominent commentators, including Al Gore (1992) and Paul Ehrlich (Ehrlich & Ehrlich, 1991).

The notion of injecting captured CO_2 into the deep ocean is another carbon-storage approach with promise, in part because the oceans have the capacity to store a large share of the CO_2 currently being emitted into the atmosphere. However, strong public opposition to engineered ocean storage has prevented R&D projects that involve direct injection and dispersal of CO_2 into the deep oceans (de Figueiredo et al. 2003). Nevertheless, research efforts and interest in the potential for ocean storage continues, particularly in countries like Japan where geologic reservoirs do not exist.

The carbon-storage option that has received the most attention recently is geologic storage, the approach incorporated into CCS. Geologic storage involves the use of depleted oil and gas reservoirs, unminable coal seams, and deep saline aquifers (Holloway, 1997; Holloway, 2001; Bruant et al. 2002; Anderson & Newell, 2004; Metz et al. 2005). Several actual projects (Sleipner in the North Sea, Weyburn in Saskatchewan, and In Salah in Algeria) have begun to demonstrate the safe and secure underground storage of CO_2 (Metz et al. 2005). While unresolved concerns remain related to mobility of the injected gas, potential risks associated with CO_2 leakage into the active biosphere, public acceptance, siting challenges, and uneven geographic distribution of appropriate storage reservoirs, the underground injection of CO_2 has become the storage approach with the greatest large-scale potential for reducing atmospheric CO_2 concentrations (Benson et al. 2002; Chow et al. 2003; Benson, 2003). Current global estimates for geologic storage range from 1,000 to 10,000 $GtCO_2$, which when compared to current emissions is considered sufficient capacity for global CO_2 storage needs for at least the next century (Metz et al. 2005). However, appropriate carbon-storage reservoirs have highly variable regional distribution, so location in proximity to major CO_2 emissions sources is likely to be more limiting than total storage capacity.

Although geologic and oceanic carbon storage are not widely understood or accepted by the general public, exploration of these ideas within the scientific community has been ongoing since the late 1970s. The idea of capturing CO_2 from power plants and disposing of it somewhere other than the atmosphere first appeared in the scientific literature thirty years ago (Marchetti, 1977). In this early proposal, both injecting CO_2 into underground reservoirs and into the deep oceans to bypass the slow kinetics of ocean-atmosphere equilibration were suggested. It was not until over a decade later that the first storage idea relying on a chemical conversion of the CO_2 gas into a carbonate solid was proposed (Seifritz, 1990).

Each of these carbon-storage approaches has different technical challenges, is associated with different levels of implementation readiness, has different constituents working on advancing the concepts, and, therefore, has different factors influencing development. While this paper focuses on geologic CCS, several of the factors discussed below have influenced each of the various carbon-storage approaches.

An engineered geologic CCS system includes four basic steps with different technologies required for each: (1) capture the CO_2 from a power plant or other concentrated stream through chemical or physical absorption, (2) transport the CO_2 gas from the capture location to an appropriate storage location, (3) inject the CO_2 gas into an underground reservoir, and (4) monitor the injected CO_2 to verify its storage (Socolow, 2005). Each storage approach involves different technological components for capturing, transporting, and storing CO_2 and the various methods are at differing levels of technical readiness (Figure 1). Several configurations of a complete CCS system rely only on the integration and scaling-up of existing commercial technologies. For instance, CO_2 capture technology is already widely used in several industrial-manufacturing processes as well as in oil refining and gas processing. Moreover, transportation of CO_2 through pipelines and injection of it underground has been occurring for decades in the United States where the gas is used to enhance oil production of declining wells. In addition, new and emerging technologies associated with CCS are currently in development. Socolow (2005), Anderson & Newell (2004), and IEA (2004) provide detailed analysis of some of these strategies.

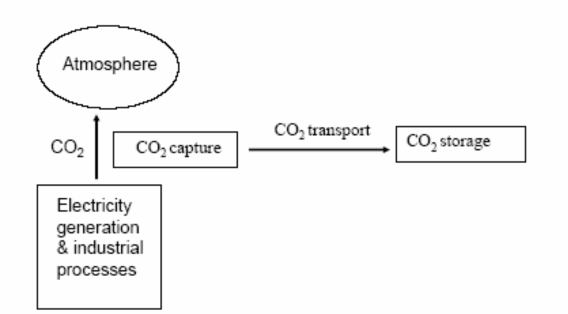

Figure 1 Technology to capture, transport, and store CO_2 is available and being currently used in other industrial applications.

Influential Nongovernmental Stakeholders

Broadly speaking, the expansion in interest over the last twenty years in CCS has occurred in response to strengthening scientific evidence implicating rising atmospheric CO_2 concentrations as the dominant contributor to climate change. These findings, coupled with an associated increase in awareness of the climate-change problem, have forced thorough examination of how to stabilize CO_2 concentrations in the atmosphere while satisfying increased energy demand. In addition to expanding energy production from renewable sources and low-carbon fuels and improving energy efficiency and conservation measures, many analysts are recognizing that CCS has potential for cost-competitive large-scale reductions of atmospheric CO_2 (Parson & Keith, 1998; Herzog, 2001; Metz et al. 2005). While the general public remains largely unaware of CCS options (Palmgren et al. 2004; Shackley et al. 2004), interest from the fossil-fuel industries and some sections of the scientific community has been influential in the recent advancement of these technologies. The following section reviews these factors and explores the small, but not inconsequential, role that environmental advocacy groups have played.

Increased Interest in the Fossil-Fuel Industry

Interest and investment in CCS has been growing in the fossil-fuel industry, particularly oil and gas companies. During the 1980s and much of the 1990s, many corporate managers, frightened by what climate change could mean to the future of their companies, publicly denied the problem and actively supported research and public campaigns that highlighted uncertainties and weaknesses in the theory of anthropogenic climate change (Levy & Rothenberg, 1999; Kolk & Levy, 2001; Gelbspan, 2004). As the scientific case strengthened during the mid to late 1990s, some firms shifted their strategy away from denial (Kolk & Levy, 2001). This shift was stronger and occurred earlier in European-based multinational companies than it did in United States-based firms (Levy & Newell, 2000; Rowlands, 2000). With this change in corporate strategy, an expansion of interest and investment in R&D of carbon-storage options has occurred. Many companies realized that the possibility of CCS weakened the link between fossil fuels and CO_2 driven climate change. The prospect of CCS reduced the threat of climate change mitigation efforts to fossil-fuel industries and made it possible to consider a fossil-based global economy throughout the next century even if controls on CO_2 emissions were instituted (Keith & Parson, 2000). The concept of CCS has, therefore, helped the fossil-fuel industries, as well as nations rich in coal, oil, and natural gas, to accept and agree to confront climate change because it allows them to perceive a future that reconciles continued use of fossil fuels in a carbon-constrained world.

Oil and gas companies, in particular, have become very interested in geologic carbon storage because they are familiar with the technologies for dealing with underground reservoirs and CO_2 injection, a well-established industry technique for enhanced oil recovery (EOR) (Hill, 2005). In mature wells with declining oil production CO_2 injection loosens up residual oil for extraction (van Bergen et al. 2003). Oil companies are therefore already knowledgeable about many critical technologies associated with underground carbon storage. Combining EOR with geologic carbon storage provides low-cost early deployment opportunities for gaining experience with CCS (Holtz et al. 2001; Stevens et al. 2001; van Bergen et al. 2003; Metz et al. 2005).

The Norwegian national oil company Statoil was the first petroleum producer to inject CO_2 underground for storage. The firm has been injecting CO_2 into a geologic formation under the North Sea since 1996. Managers were motivated to store rather than emit the CO_2 extracted from a natural gas stream by a Norwegian tax on the release of CO_2 into the atmosphere (Torp & Brown, 2002). The other currently operating large-scale geologic storage projects are at Weyburn in the Canadian province of Saskatchewan, where CO_2 has been injected underground since 2000 for the dual purpose of enhancing oil recovery and storage, and In Salah (Algeria) where the first large-scale injection of CO_2 into a gas reservoir began in 2004 (Metz et al. 2005). The In Salah project is a joint venture involving Sonatrach (the national oil company of Algeria), BP, and Statoil.

In addition to the In Salah initiative, BP is currently planning, and has begun investing in, at least two other CO_2 storage projects—one off the coast of Scotland and another in California. BP stands out among oil companies through investing heavily in the development and demonstration of geologic CO_2 storage. Interestingly, these BP carbon-storage projects are not economically justifiable in the short term. The company has chosen to fund these initiatives to advance the technology without any direct and immediate economic benefits, but clearly it is aiming to position itself as an industry leader in this area.

Frustration within the Scientific Community on Climate Action

Scientists and engineers who feel a growing sense of urgency about climate change form another influential group of stakeholders that has advanced CCS technology. An expanding segment of this community believes reducing atmospheric CO_2 concentrations to limit climate change is desperately needed. This strong concern is coupled with associated frustration at the lack of effective policy. Although empirical evidence is mounting, world leaders have been slow to take action to stabilize atmospheric CO_2 concentrations, leaving scientists increasingly frustrated and motivated to consider technical rather than political solutions. When faced with the social, economic, and political barriers preventing the implementation of national and international policies to reduce greenhouse-gas emissions, scientists and engineers have looked to deliberate carbon storage as another pathway to action—a pathway that is more open to their involvement. This influence from the frustrated scientific community can be identified in a plethora of articles in high-profile scientific journals, only a sampling of which are referenced here (Abelson, 2000; Hoffert et al. 2002; Caldeira et al. 2003; Pacala & Socolow, 2004; Spotts, 2004; Holdren, 2006).

Minimal Public Awareness and the Role of Environmental Advocacy Groups

Throughout the recent period of rapidly growing interest in CCS, it has been acknowledged that public acceptance will influence ultimate advancement and deployment. Nevertheless, public perception of these technologies remains limited. Studies at the Tyndall Centre in the United Kingdom using focus groups and surveys indicate that with adequate information about the climate-change context, the public may look favorably on CCS (Gough et al. 2002; Shackley et al. 2004). A study conducted in the United States, however, using personal interviews and a survey, suggests that Americans may be more skeptical and less accepting than the British public (Palmgren et al. 2004). The study urges careful consideration in devising strategies to inform people about the technology and suggests that how the public debate gets framed will be critical in determining popular perceptions (Palmgren et al. 2004).

Environmental advocacy groups play a critical role in shaping public debate about how best to address environmental problems, so how these organizations portray CCS is likely to influence public reactions. To date, their role regarding carbon storage has been mixed (Stephens & Verma, 2006). While one leading American environmental group, the Natural Resources Defense Council (NRDC), has taken a strong position supporting the development and demonstration of CCS technologies (Hawkins, 2003; 2005), many other organizations, both national and international, have had reservations about the environmental as well as political implications of CCS (Hawkins, 2001; Union of Concerned Scientists, 2001; Greenpeace, 2005; World Wildlife Fund, 2005).

Although public opposition to CCS has been anticipated, little actual resistance has emerged and environmental advocacy groups have been relatively quiet on the issue.[1] Despite the rapid advancement of demonstration projects, the environmental community has not voiced a strong position for or against the geologic storage of CO_2. Organized environmentalism seems to be trying to balance cautious hesitancy of this “end-of-pipe” “geoengineering” approach with practical acceptance that such carbon-management technologies may be needed to supplement other stabilization measures. Moreover, pervasive resistance to novel technologies within the environmental movement is recognized, and recent work has identified the challenges of overcoming this opposition (Cohen, 2006). Public opposition to the idea of underground storage may be presently minimized due to some awareness (in parts of the world at least) of the successful history of injecting CO_2 underground to enhance oil recovery.

Despite the potential that environmental advocacy groups have to influence the public perception of CCS, in the past 15 years these organizations have facilitated minimal public engagement on the subject

[1] CCS poses some of the same challenges to organized environmentalism as the debate over nuclear power in the balance between the necessity of climate-change action and a fear of technology and its unintended consequences.

and they have not developed a strong and consistent public message. This lack of a position regarding geologic storage has likely contributed to the limited public awareness (Verma & Stephens, 2006).

Division regarding CCS technology can be viewed as representative of the larger challenges facing environmental advocacy groups as they struggle to adjust to the unique and daunting challenges of climate change. There has been a great deal of discussion about the capacity of mainstream environmental organizations in the United States to engage meaningfully on the climate-change issue in the past few years as weaknesses in their response have been identified (McCright & Dunlap, 2000; 2003).

While some division has emerged surrounding the advancement of CCS technology, environmental advocacy groups have been generally supportive of terrestrial carbon sequestration, in part due to other indirect associated environmental benefits of managing land use to maximize carbon uptake (Manion, 2004). Nevertheless, the international environmental community has been strongly opposed to the inclusion of terrestrial carbon sequestration in the Kyoto Protocol due to large uncertainties regarding the continued existence of carbon sinks associated with forests and land-use changes.

In contrast, the idea of ocean storage has not been received well by environmental organizations or the general public. Strong public opposition prevented a collaborative research project involving direct injection of CO_2 into the deep ocean off the coast of Hawaii (de Figueiredo et al. 2003). Despite the development of a public-outreach plan, this case exemplifies a complex mix of emotions contributing to the pattern of opposition, including fear, isolation from the decision-making process, and passion to protect the sanctity of the oceans. Although most of the CO_2 emitted from human activity will eventually end up in the oceans, based on the strength of opposition in this case and a few others, it seems unlikely that the idea of deliberate oceanic injection of CO_2 will become socially acceptable.

Governmental Influence

Governmental influence on this pattern of increased activity regarding CCS technology can be divided into three categories: (1) political positions and strategy, (2) governmental support of R&D, and (3) economic policy tools and international treaties. This section explores each of these groupings with an eye to identifying examples of influence.

Political Positions and Strategy

A political position that supports the advancement of CCS technology as an alternative to regulations to limit CO_2 emissions has clearly influenced CCS development. Nevertheless, proposed CCS approaches were not developed with the intent of eliminating the need for emissions regulations, but, given the magnitude of the CO_2 problem, are largely viewed as a supplement (Pacala & Socolow, 2004). Within the political arena, however, support for CCS is often perceived as an alternative to regulating CO_2 releases. The current United States administration has opposed any national regulation to reduce CO_2 emissions (see e.g., Abraham, 2004), but growing public concern about climate change has forced it to confront the issue and to define actions to mitigate the problem. Supporting CCS as part of the President's Advanced Energy Initiative appears to be a politically convenient way to demonstrate action on climate change without making policy decisions to ensure actual CO_2 emissions reduction (NEC, 2006).

The leadership of UK Prime Minister Tony Blair is another important factor contributing to interest in CCS technologies. In addition to being the world leader pushing hardest to reduce greenhouse-gas emissions, in his role as G8 chairman in 2005, Blair advocated for increased governmental support for carbon abatement as a critical part of addressing climate change (Blair, 2003). Recognizing the importance of American involvement in any strategy to tackle the global problem of climate change, Blair has persistently tried to change the Bush administration's position. This focus on advancing technology rather than pushing for emission-reduction policies can be interpreted as an attempt to find common ground with the United States.

Governmental Support of Research and Development

Governmental efforts to advance the development of CCS technologies through R&D support vary considerably among countries. The potential impact of the successful deployment of CCS systems is related to a region's endemic fossil-fuel resources and level of fossil-fuel energy reliance. As a result, different national priorities are apparent when looking at government-supported CCS research programs.

In the coal-rich, energy-hungry United States, CCS provides the only way to reconcile increased use of domestic coal with climate-change mitigation, so the American government increasingly touts CCS as part of the future energy infrastructure. The federal government currently supports a suite of CCS R&D programs and has also initiated a large-scale demonstration project named FutureGen. The primary goal of the core CCS R&D program in the United States is to support technological developments that will reduce costs; the Regional Sequestration Partnership Program supports region-specific studies to determine the most suitable CCS technologies, regulations, and infrastructure. The FutureGen initiative is a US$1 billion project planned as the first demonstration of a commercial scale coal-fired power plant that captures and stores CO_2. The goal is to establish technical feasibility and economic viability for integrating coal gasification technology (IGCC) with CCS. Although the FutureGen project began in 2003, selection of the location for this power plant is not due to occur until late 2007.

European governments have also supported CCS technology advancement in several ways. The European Community (EC) contributed funds to several CCS projects through its Sixth Framework Programme (FP6, totaling an EC contribution of €35 million during the first proposal round) building on the research done under FP4 and FP5 during the early 1990s that initiated European R&D into CCS. This support includes contributions to the Sleipner project as well as to some other R&D and small-scale demonstration projects. Independently of Brussels, EC member states are also providing modest support for CCS R&D. For instance, the British government recently announced a €40 million fund to support CO_2 storage in depleted North Sea oil and gas fields. Japan is another country that has been actively encouraging CCS. Interestingly, lacking suitable land-based geologic reservoirs, Japan has focused most of its investment on the potential and limitations of oceanic CO_2 storage. Most developing countries have not begun to seriously consider the potential of CCS technologies as a climate change mitigation strategy, so government support for advancing this set of technologies has been minimal or nonexistent.[2]

Recognizing the varied efforts in advancing CCS technology around the world, the United States initiated an international body, the Carbon Sequestration Leadership Forum (CSLF), in 2003. The CSLF provides a forum for collaboration by facilitating joint projects, as well as providing a mechanism for multilateral communication regarding the latest CCS developments and a venue for formulating strategies to transfer technology to developing countries.

In addition to the direct impact that government-supported R&D has on the advancement of CCS, public sponsorship motivates involvement of individuals and companies (Stephens & Zwaan, 2005).

Economic Policy Tools and International Treaties

Governmental activity including the use of economic policy tools and involvement in international treaties has also influenced CCS development by altering perceptions of the relative costs associated with reducing CO_2 emissions versus the costs of storing CO_2. This section explains how the imposition of a carbon tax in Norway directly motivated the first large-scale geologic carbon-storage project beneath the North Sea and how the creation of the Kyoto Protocol's framework for national accounting of carbon sources and sinks influenced the advancement of CCS by highlighting the economic value of carbon storage.

In 1996, the Norwegian government instituted a levy on CO_2 emissions equivalent to approximately US$40/t$CO_2$ that motivated Statoil, the national oil company, to capture the CO_2 emitted from their Sleipner oil and gas field and inject it into an underground formation rather than continue to emit it to the atmosphere (Torp & Brown, 2002). The Sleipner project has had a dramatic impact on the understanding of geologic carbon storage and CCS because researchers from around the world have been monitoring and learning from this pioneering initiative that has successfully been injecting and storing about one million tons of CO_2 per year for the past nine years (Gale et al. 2001). Other governmental economic policy tools, including the European Union emissions trading scheme, have also provided investment incentives for CCS projects (Hasselknippe & Roine, 2006).

A more indirect example of governmental activity influencing CCS development relates to the Kyoto Protocol negotiations. Although the accord in its current form does not include any credit provisions for carbon stored through CCS projects, ongoing discussions have raised awareness of the value of carbon storage. Interest in regional potentials, particularly for terrestrial storage, increased dramatically during the development of the climate-change agreement and associated negotiations about its framework for national accounting of carbon sources and sinks. Initial adoption of the Kyoto Protocol in 1997 committed industrialized nations to legally binding greenhouse-gas reductions. However, contentious negotiations on whether carbon sinks, including forests, should be counted toward reduction targets ensued for several years (IGBP, 1998). On one hand, the United States, Japan, Canada, New Zealand, and Australia supported counting carbon storage associated with forest growth toward meeting their emission-reduction goals. On the other hand, European countries, which have fewer forested tracts, felt that the Kyoto commitments should be met only with direct emission reductions, not through the identification of offsetting carbon sinks. Although the debate focused on terrestrial sequestration, the process increased awareness about the value of carbon storage more generally. Also during this period, research

[2] India has agreed to contribute US$10 million to the United States Department of Energy's FutureGen project.

designed to improve understanding and to quantify the potential of all storage methods increased.

Although the United States did not ratify the Kyoto Protocol, the accounting for terrestrial carbon sinks to offset emission reductions (that the country's delegates ironically championed in negotiations) is included in the agreement now in force (Victor, 2004). Within the agreement, each Annex I nation is responsible for verifying its own carbon-emission reductions and accounting for terrestrial carbon storage within its boundaries. While terrestrial sequestration is currently included in the Kyoto Protocol's Clean Development Mechanism (CDM) (which provides for transferable credit to industrialized countries that invest in projects to avoid emissions in developing countries lacking targets) current negotiations are defining how geologic and oceanic storage projects might be included (Haines et al. 2004; Hohne, 2006).

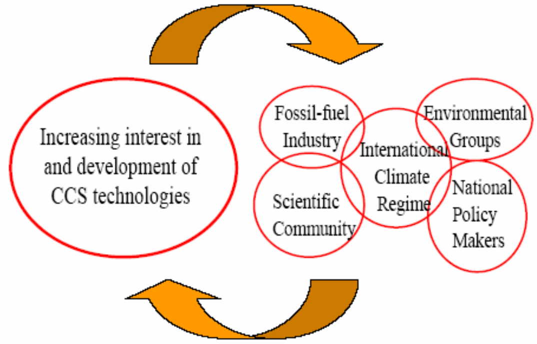

Figure 2 Schematic illustration depicting an influence from various factors supporting increased interest in and develop-ment of CCS technologies. This figure also demonstrates reciprocal relationships in which the increased interest and development of CCS has influenced the actions, percep-tions, and strategies of various critical stakeholders in the societal debate on how to confront climate change.

Conclusion

The rapidly growing interest in and development of CCS technologies has evolved in tandem with ongoing discussions about how society should respond to the risks of climate change. Attempting to compare the various governmental and nongovernmental influences on CCS advancement is beyond the scope of this paper, but is an important area for future research. The various interconnected social factors influencing the advancement of these technologies highlight the complexity of integrating developments in science and engineering into sustainable practices.

A valuable complement to the work presented here would be to identify how the prospect of deploying CCS technologies on a larger scale has influenced the positions, strategies, priorities, and actions of key stakeholders and institutions involved in the debate about how best to mitigate climate-change risks. Figure 2 is a schematic illustration depicting various influences contributing to increased interest in and development of CCS technologies. This figure also demonstrates reciprocal relationships in which growing CCS interest and development has in turn shaped the perceptions, strategies, and actions of various stakeholders. More detailed research would be valuable to identify how expanded attention to CCS has influenced actors with a strong voice on climate change. Methods that could be useful in exploring these reciprocal relationships include interviews with various stakeholders and media analysis.

Despite widespread recognition of the need for a shift in our energy infrastructure to no- or low-carbon technologies to stabilize atmospheric CO_2 concentrations (Hoffert et al, 2002; Pacala & Socolow, 2004; Holdren, 2006), movement in this direction has been slow and uncertain (Sagar & Gallagher, 2004; Neuhoff, 2005; Stephens & Zwaan, 2005). While research exploring the challenges of energy-technology diffusion has focused on economic and technical aspects (Isoard & Soria, 2001; Grubler et al. 2002; Nakicenovic, 2002), and generally concentrates on the national scale (NCEP, 2004; Nemet & Kammen, 2007), often overlooked is the complex socio-political context within which new technologies must be integrated. One approach to future research could involve incorporating analysis of the context of CCS development with the emerging literature on transition management. This perspective recognizes the complexity of transitions, including the interactions, interdependencies, and feedbacks among different actors, technologies, infrastructures, and institutions (Kemp et al. 1998; Rotmans et al. 2001; Kemp & Loorbach, 2003; Loorbach & Rotmans, 2006).

Several recent studies have enhanced this body of literature by suggesting different approaches to induce learning for a societal shift in sustainable-energy technologies, including visioning and scenario building (Berkhout et al. 2002), national-dialogue promotion (Vergragt, 2006), and small-scale, bounded experimentation with emerging technologies (Brown et al. 2003; Brown & Vergragt, 2006). Applying these approaches to CCS technologies could contribute a valuable new dimension to both the theory and practice of transition management with energy technologies.

Understanding the evolution of interest in this specific set of highly novel and uncertain technologies has broader implications for how social influences steer technological innovation and shifts in technological norms. Despite the somewhat controversial nature of CCS technologies and their associated imponderables, interest in these approaches has grown as the challenge of reconciling energy demand and climate-change mitigation becomes evermore daunting. The attention focused on CCS is likely to expand in coming years because the value associated with the potential reduction in the atmospheric concentration of CO_2 will increase as human society continues to postpone action to mitigate climate change.

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References

Abelson, P. 2000. Limiting atmospheric CO_2. *Science* 289 (5483):1293.

Abraham, S. 2004 The Bush administration's approach to climate change. *Science* 305(5684):616–617.

Anderson, S. & Newell, R. 2004. Prospects for carbon capture and storage technologies. *Annual Review of Environment and Resources* 29:109–42.

Benson, S., Hepple, R., Apps, J., Tsang, C., & Lippman, M. 2002. *Comparative Evaluation of Risk Assessment, Management, and Mitigation Approaches for Deep Geologic Storage of CO_2*. Lab Report LBNL-51170. Berkeley: Earth Sciences Division, Lawrence Berkeley National Laboratory.

Benson, S. 2003. *Carbon Sequestration: Potential and Risks*. Workshop on Novel Approaches to Carbon Management. February 12, Irvine, CA: National Research Council.

Berkhout, F., Hertin, J., & Jordan, A. 2002. Socio-economical futures in climate change impact assessment: using scenarios as "learning machines." *Global Environmental Change A* 12(2):83–95.

Blair, T. 2003. Meeting the sustainable development challenge. *Environment* 45(4):20–26.

Brown, H., Vergragt, P., Green, K., & Berchicci, L. 2003. Learning for sustainability transition through bounded socio-technical experiments in personal mobility. *Technology Analysis and Strategic Management* 13(3):298–315.

Brown, H. & Vergragt, P. 2006. Bounded socio-technical experiments as agents of systemic change: the case of a zero-energy residential building. *Technological Forecasting and Social Change* Published Online: July 3.

Bruant, R., Celia, M., Guswa, A., & Peters, C. 2002. Safe storage of CO_2 in deep saline aquifers. *Environmental Science and Technology* 36(11):240A–245A.

Caldeira, K., Jain, A., & Hoffert, M. 2003. Climate sensitivity uncertainty and the need for energy without CO_2 emissions. *Science* 299(5653):2052–2054.

Chow, J., Watson, J., Herzog, A., Benson, S., Hidy, G., Gunter, W., Penkala, S., & White, C. 2003. Separation and capture of CO_2 from large stationary sources and sequestration in geological formations. *Journal of Air and Waste Management Association* 53(10):1172–1182.

Cohen, M. 2006. Ecological modernization and its discontents: can the American environmental movement overcome its resistance to technology? *Futures* 38(6):528–547.

de Figueiredo, M., Reiner, D., & Herzog, H. 2003. Ocean carbon sequestration: a case study in public and institutional perceptions. In J. Gale & Y. Kaya (Eds.), *Greenhouse Gas Control Technologies* (GHGT-6). pp. 799–804. Oxford: Permagon.

Ehrlich, P. & Ehrlich, A. 1991. *Healing the Planet, Strategies for Resolving the Environmental Crisis*. Reading, MA: Addison-Wesley.

Gale, J., Christensen, N., Cutler, A., & Torp, T. 2001. Demonstrating the potential for geological storage of CO_2: the Sleipner and GESTCO projects. *Environmental Geosciences* 8(3):160–165.

Gelbspan, R. 2004. *Boiling Point: How Politicians, Big Oil and Coal, Journalists, and Activists Are Fueling the Climate Crisis–and What We Can Do to Avert Disaster*. New York: Basic Books.

Gore, A. 1992. *Earth in the Balance: Ecology and the Human Spirit.* Boston: Houghton Mifflin.

Gough, C., Taylor, I., & Shackley, S. 2002. Burying carbon under the sea: an initial exploration of public opinion. *Energy and Environment* 13(6):883–900.

Greenpeace. 2005. Limits of Carbon Capture and Storage in Combating Climate Change. http://www.greenpeace.org/international/press/releases/carboncaptureandstoragereport April 20, 2006.

Grubler, A., N. Nakicenovic, & W. Nordhaus (Eds.). 2002. *Technological Change and the Environment.* Washington, DC: Resources for the Future Press.

Haines, M., Reeve, D., Russell, D., Ribas, A., & Varilek, M. 2004. *Use of the Clean Development Mechanism for CO_2 Capture and Storage.* Seventh International Greenhouse Gas Control Technology Conference. September 5–9. Vancouver.

Hasselknippe, H. & Roine, K. 2006. *Carbon 2006 Report.* Oslo: Point Carbon.

Hawkins, D. 2001. *Stick it Where??—Public Attitudes toward Carbon Storage.* First National Conference on Carbon Sequestration. National Energy Technology Laboratory, Washington, DC. http://www.netl.doe.gov/publications proceedings/01/carbon_seq/1c2.pdf.

Hawkins, D. 2003. Passing gas: policy implications for geologic carbon storage sites. In J. Gale & Y. Kaya (Eds.), *Greenhouse Gas Control Technologies* (GHGT-6). pp. 249–254. Oxford: Permagon.

Hawkins, D. 2005. CO_2 Capture and Storage: Just Do It. http://www.usea.org/Ericeprogram/Presentations-Remarks/Hawkins%201100.pdf. March 15, 2006.

Herzog, H. 2001. What future for carbon capture and sequestration? *Environmental Science & Technology* 35(7):148A–153A.

Hill, G. 2005. *Moving to Utilize Carbon Capture/Sequestration Technologies–A Path Forward to Reduce CO_2 Emissions*. Fourth Annual Conference on Carbon Capture and Sequestration. May 2–5, U. S. Department of Energy, Alexandria, VA.

Hoffert, M., Caldeira, K., Benford, G., Criswell, D., Green, C., Herzog, H., Jain, A., Kheshgi, H., Lackner, L., Lewis, J., Lightfoot, H., Manheimer, W., Mankins, J., Mauel, M., Perkins, L., Schlesinger, M., Volk, T., & Wigley, T. 2002. Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science* 298(5595):981–987.

Hohne, N. 2006. *What is Next After the Kyoto Protocol: Assessment of Options for International Climate Policy, Post 2012.* Amsterdam: Techne Press.

Holdren, J. 2006. The energy innovation imperative, addressing oil dependence, climate change, and other 21st century energy challenges. *Innovations, Technology, Governance & Globalization* 1(2):3–23.

Holloway, S. 1997. An overview of the underground disposal of carbon dioxide. *Energy Conversion and Management* 38(Supp):S193–S198.

Holloway, S. 2001. Storage of fossil fuel-derived carbon dioxide beneath the surface of the earth. *Annual Review of Energy and the Environment* 26:145–166.

Holtz, M., Nance, P., & Finley, R. 2001. Reduction of greenhouse gas emissions through CO_2 EOR in Texas. *Environmental Geosciences* 8(3):187–199.

International Energy Agency (IEA). 2004. *Prospects for CO_2 Capture and Storage*. Paris: Organization for Economic Cooperation and Development and IEA.

International Geosphere–Biosphere Programme (IGBP). 1998. The terrestrial carbon cycle: implications for the Kyoto Protocol. *Science* 280(5368):1393–1394.

Isoard, S. & Soria, A. 2001. Technical change dynamics: evidence from the emerging renewable energy technologies. *Energy Economics* 23(6):619–636.

Jackson, R., Jobbagy, E., Avissar, R., Roy, S., Barrett, D., Cook, C., Farley, K., le Maitre, D., McCarl, B., & Murray, B. 2005. Trading water for carbon with biological carbon sequestration. *Science* 310(5756):1944.

Keith, D. & Parson, E. 2000. A breakthrough in climate change policy? *Scientific American* 282(2):78–79.

Kemp, R., Schot, J., & Hoogma, R. 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. *Technology Analysis and Strategic Management* 10(2):175–195.

Kemp, R. & Loorbach, D. 2003. *Governance for Sustainability Through Transition Management.* Open Meeting of the Human Dimensions of Global Environmental Change Research Community. October 16–19, Montreal.

Kolk, A. & Levy, D. 2001. Winds of change: corporate strategy, climate change and oil multinationals. *European Management Journal* 19(5):501–509.

Kueppers, L., Baer, P., Harte, J., Haya, B., Koteen, L., & Smith, M. 2004. A decision matrix approach to evaluating the impacts of land-use activities undertaken to mitigate climate change. *Climatic Change* 63(3):247–257.

Lenton, T. & Huntingford, C. 2003. Global terrestrial carbon storage and uncertainties in its temperature sensitivity examined with a simple model. *Global Change Biology* 9(10):1333–1352.

Levy, D. & Rothenberg, S. 1999. *Corporate Strategy and Climate Change: Heterogeneity and Change in the Global Automobile Industry.* BCSIA Discussion Paper E-99-13. Cambridge: Environment and Natural Resources Program, Harvard University. http://www.ksg.harvard.edu/gea/pubs/e-99-13.htm.

Levy, D. & Newell, P. 2000. Oceans apart? Business responses to the environment in Europe and North America. *Environment* 42(9):8–20.

Loorbach, D. & Rotmans, J. 2006. Managing transitions for sustainable development. In A. Wieczorek & X. Olsthoorn (Eds.), *Understanding Industrial Transformation.* pp. 75–98. New York: Springer.

Manion, M. 2004. How it works: forest carbon sequestration. *Catalyst* 3(2). http://www.ucsusa.org/publications/catalyst/fa04-catalyst-forest-carbon-sequestration.html.

Marchetti, C. 1977. On geoengineering and the CO_2 problem. *Climatic Change* 1(1):59–68.

McCright, A. & Dunlap, R. 2000. Challenging global warming as a social problem: an analysis of the conservative movement's counter-claims. *Social Problems* 47(4):499–522.

McCright, A. & Dunlap, R. 2003. Defeating Kyoto: the conservative movement's impact on the U.S. climate change policy. *Social Problems* 50(3):348–373.

Metz, B., O. Davidson, H. de Coninck, M. Loos, & L. Meyer (Eds.). 2005. *Carbon Dioxide Capture and Storage.* IPCC Special Report. Intergovernmental Panel on Climate Change Working Group III. http://www.ipcc.ch/activity/srccs/index.htm

Mutuo, P., Cadisch, G., Albrecht, A., Palm, C. & Verchot, L. 2005. Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. *Nutrient Cycling in Agroecosystems* 71(1):43–54.

Nakicenovic, N. 2002. Technological change and diffusion as a learning process. In A. Grubler, N. Nakicenovic, & W. Nordhaus (Eds.), *Technological Change and the Environment.* pp. 160–181. Washington, DC: Resources for the Future Press.

National Commission on Energy Policy (NCEP). 2004. *Ending the Energy Stalemate: a Bipartisan Strategy to Meet America's Energy Challenges*. Washington, DC: NCEP. http://www.energycommission.org/files/contentFiles/report_noninteractive_44566feaabc5d.pdf.

National Economic Council (NEC). 2006. *Advanced Energy Initiative.* Washington, DC: The White House NEC. http://www.whitehouse.gov/stateoftheunion/2006/energy/energy_booklet.pdf.

Nemet, G. & Kammen, D. 2007. U.S. energy research and development: declining investment, increasing need, and the feasibility of expansion. *Energy Policy* 35(1):746–755.

Neuhoff, K. 2005. Large-scale deployment of renewables for electricity generation. *Oxford Review of Economic Policy* 21(1):88–110.

Pacala, S. & Socolow, R. 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science* 305(5686):968–972.

Palmgren, C., Morgan, C., de Bruin, W., & Keith, D. 2004. Initial public perceptions of deep geological and oceanic disposal of carbon dioxide. *Environmental Science and Technology* 38 (24):6441–6450.

Parson, E. & Keith, D. 1998. Climate change: fossil fuels without CO_2 emissions. *Science* 282(6):1053–1054.

Rotmans, J., Kemp, R., & van Asselt, M. 2001. More evolution than revolution: transition management in public policy. *Foresight* 3(1):15–31.

Rowlands, I. 2000. Beauty and the beast? BP's and Exxon's positions on global climate change. *Environment and Planning C* 18(3):339–354.

Sagar, A. & Gallagher, K. 2004. Energy technology demonstration and deployment. In *Ending the Energy Stalemate: A Bipartisan Strategy to Meet America's Energy Challenges*. p. 117. Washington, DC: National Commission on Energy Policy.

Seifritz, W. 1990. CO_2 disposal by means of silicates. *Nature* 345(6275):486.

Shackley, S., McLachlan, C., & Gough, C. 2004. *The Public Perceptions of Carbon Capture and Storage.* Tyndall Centre Working Paper 44. Manchester: Tyndall Centre for Climate Change Research. http://www.tyndall.ac.uk/publications/working_papers/wp44.pdf.

Socolow, R. 2005. Can we bury global warming? *Scientific American* 293(1):49–55.

Spotts, P. 2004. Stabilizing the global 'greenhouse' may not be so hard. *The Christian Science Monitor.* August 13.

Stevens, S., Kuuskraa, V., Gale, J., & Beecy, D. 2001. CO_2 injection and sequestration in depleted oil and gas fields and deep coal seams: worldwide potential and costs. *Environmental Geosciences* 8(3):200–209.

Stephens, J. & van der Zwaan, B. 2005. The case for carbon capture and storage. *Issues in Science and Technology* 22(1):69–76.

Stephens, J. & Verma, P. 2006. *The Role of Environmental Advocacy Groups in the Advancement of Carbon Capture and Storage (CCS).* Fifth Annual Conference on Carbon Capture & Sequestration. May 8–11, U.S. Department of Energy, Alexandria, VA.

Torp, T. & Brown, K. 2002. *CO_2 Underground Storage Costs as Experienced at Sleipner and Weyburn*. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. September 5–9, Vancouver.

Union of Concerned Scientists. 2001. Policy Context of Geologic Carbon Sequestration. http://www.ucsusa.org/assets/documents/global_warming/GEO_CARBON_SEQ_for_web.pdf. March 15, 2006.

van Bergen, F., Wildenborg, A., Gale, J., & Damen, K. 2003. Worldwide selection of early opportunities for CO_2-EOR and CO_2-ECBM. In J. Gale & Y. Kaya (Eds.), *Greenhouse Gas Control Technologies* (GHGT-6). pp. 639–644. Oxford: Permagon.

Vergragt, P. 2006. *Towards a National Policy Dialogue on Hydrogen in the USA*. Ninth International Conference on Technology Policy and Innovation: Science, Society, and Sustainability. June 18–21, Santorini, Greece.

Verma, P. & Stephens, J. 2006. *Environmental Advocacy Groups' Perspectives on Carbon Capture and Storage.* Climate Change Technology Conference: Engineering Challenges and Solutions in the 21st Century. May 10–12, Engineering Institute of Canada, Ottawa.

Victor, D. 2004. *The Collapse of the Kyoto Protocol and the Struggle to Slow Global Warming.* Princeton: Princeton University Press.

Winjum, J., Dixon, R., & Schroeder, P. 1992. Estimating the global potential of forest and agroforest management practices to sequester carbon. *Water, Air, and Soil Pollution* 64(1–2):213–227.

World Wildlife Fund. 2005. More Questions than Answers on Carbon Capture and Storage. http://www.wwf.ca/AboutWWF/WhatWeDo/ConservationPrograms/RESOURCES/PDF/css_statement.pdf. March 16, 2006.

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ARTICLE

Sustainability and resilience: toward a systems approach

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A comprehensive systems approach is essential for effective decision making with regard to global sustainability, since industrial, social, and ecological systems are closely linked. Despite efforts to reduce unsustainability, global resource consumption continues to grow. There is an urgent need for a better understanding of the dynamic, adaptive behavior of complex systems and their resilience in the face of disruptions, recognizing that steady-state sustainability models are simplistic. However, assessing the broad impacts of policy and technology choices is a formidable challenge, as exemplified in life-cycle analysis of the implications of alternative energy and mobility technologies. A number of research groups are using dynamic modeling techniques, including biocomplexity, system dynamics, and thermodynamic analysis, to investigate the impacts on ecological and human systems of major shifts such as climate change and the associated policy and technology responses. These techniques can yield at least a partial understanding of dynamic system behavior, enabling a more integrated approach to systems analysis, beneficial intervention, and improvement of resilience. Recommendations are provided for continued research to achieve progress in the dynamic modeling and sustainable management of complex systems.

KEYWORDS*:* decision models, ecosystem analysis, biocomplexity, appropriate technology, globalization, population-environment relationship

Introduction

Global policymakers and strategic planners face difficult choices—for example, what future energy sources will power cities, businesses, and transport systems? Is it possible to sustain economic growth and avoid major disruptions or ecological impacts? Our premise is that the effective pursuit of global sustainability requires a *systems approach* to the development of policies and intervention strategies. Absent a full understanding of system implications, there is a risk of unintended consequences; for instance, adoption of innovative technologies based on renewable resources (such as bio-based fuels) may have hidden adverse side effects upon agricultural productivity.

Sustainable energy and mobility are closely coupled and are essential services in the supply chain for virtually every economic sector. It has become increasingly unrealistic to perform a self-contained analysis of sustainability in a particular industry without touching upon the broader questions of energy, transportation, climate change, and urban planning. Thus, setting the boundaries for meaningful analysis has become a formidable challenge. Perhaps a more robust approach will be to explore sustainability issues within a global, integrated model, with a magnified resolution for the particular system or sector being studied.

The following discussion explores several fundamental questions:

- What is the current state of scientific knowledge about how complex industrial systems can achieve both short-term continuity and long-term ecological integrity?
- What scientific advances are needed to better understand the linked behavior of complex social, economic, and biophysical systems?
- How can this knowledge be applied to the design and management of future technologies and infrastructures required to meet human needs, particularly energy and mobility?

Drawing upon the experience and insights of intellectual leaders from academia, government, and industry, this essay seeks to provide guidance for future research and collaborative initiatives that offer pragmatic pathways toward sustainability.[1]

State of Sustainability

Over the last two decades, awareness of sustainability has increased significantly among govern-

[1] Much of the material presented here originated from a Sustainable Systems Symposium held in March, 2006 at The Ohio State University. See acknowledgement for more details.

ment, industry, and the general public. Policymakers worldwide have sought to incorporate sustainability considerations into urban and industrial development. Sustainable development and social responsibility have become increasingly important strategic issues for companies in virtually every industry. Leading manufacturers in the United States and abroad have begun to emphasize sustainability in their internal business processes, external stakeholder and investor relations, and customer value propositions. The following are examples of companies striving to adopt more sustainable business practices.

- Interface, a leading producer of industrial floor coverings, was an early adopter of sustainability principles under the leadership of Chairman and CEO Ray Anderson. By developing products using more sustainable process technologies, Interface has reduced greenhouse gas (GHG) emissions by about 50% and energy consumption by about 33% in five years. Through recovery and reuse of waste materials over a ten-year period, the company has diverted about 84 million pounds of carpet waste from landfills and avoided about US$300 million in waste disposal costs. Redesign of every aspect of Interface's products has led to a significant decrease in their life cycle-environmental impacts (Bertolucci, 2006).
- Chevron is incorporating sustainability into its business models by developing profitable approaches for meeting public energy needs without bias toward any particular technology. For example, Chevron Energy Solutions (CES) is a fast-growing provider of energy-efficient facility upgrades that are funded by energy savings and can be "bundled" with alternative power (e.g., solar, fuel cells). CES public-sector projects for Federal agencies and various municipalities are reducing resource consumption, avoiding GHG emissions, and saving taxpayer money while benefiting the environment and society. In 2005, CES projects saved 1.2 billion cubic feet of natural gas and 177 million kWh of electricity use and avoided 97,000 metric tons of carbon-dioxide emissions (Davis, 2006).
- General Motors (GM) has adopted a corporate-responsibility framework that combines social responsiveness with corporate values and business goals. Despite its recent financial difficulties, GM recognizes that social and environmental responsibility is critical to its long-term survival. In addition to incremental energy and environmental improvement goals, GM has developed a strategy for reducing fuel consumption and emissions by successive adoption of new propulsion technologies. These innovations range from near-term introduction of flex-fuel vehicles that can run on alternative fuels, to hybrid electric vehicles, to two-mode hybrid systems developed in partnership with BMW and Daimler-Chrysler, to longer-term development of hydrogen fuel cell vehicles (Cullum, 2006).

The above examples indicate advances by progressive companies in every industrial sector. Yet, paradoxically, the more efficient companies become in terms of resource use, the more rapidly the economy grows; this "rebound effect" results in a net increase in industrial society's ecological footprint (Fiksel, 2006). It is becoming apparent that voluntary, incremental environmental improvements by individual companies will be inadequate to significantly offset the growth of the global economy, and that the rapid growth of China, India, and other Asian economies will likely exacerbate this problem. Ecological-footprint analysis suggests that humanity's ecological demands already exceed what nature can supply; thus, we have arguably moved into what is termed "ecological overshoot," effectively depleting the available stock of natural capital rather than "living off the interest" (Venetoulis et al. 2004).

The question of urban system resilience is particularly urgent. By 2030 over 60% of the world's population will live in cities, many in developing countries; the urban populations of Africa, Asia, and Latin America will go from 1.9 to 3.9 billion over that period. Cities have been extraordinarily resilient; from 1100 to 1800 only 42 cities worldwide were abandoned after their destruction (Allenby & Fink, 2005). Recent incidents, including natural disasters and deliberate attacks, have increased worldwide concerns about urban vulnerability. The resulting demands for greater resilience have in many cases failed to draw from the historical record and systems analysis, and have therefore tended to seriously underestimate the difficulty of enhancing the resilience of complex, adaptive systems such as cities. It is important to develop and implement policies for enhanced resilience, since trends suggest greatly increased complexity for future urban systems (Allenby, 2005).

Need for a Systems Approach

One approach toward sustainability is offered by *industrial ecology*—a framework for shifting industrial systems from a linear model to a closed-loop model that resembles the cyclical flows of natural ecosystems. In nature, there is no waste, since one creature's wastes become another's nutrients. Thus, industrial ecology provides a foundation for rethinking conventional product or process technologies and discovering innovative pathways for recovery and reuse of waste streams in place of virgin resources. However, the practice of industrial ecology has focused mainly on *reducing unsustainability* rather than strengthening sustainability's systemic underpinnings (Ehrenfeld, 2005). Current efforts to achieve sustainability are directed largely at reducing environmental "burdens" measured in terms of resource consumption and waste emissions. Little is understood about the broader impacts of these material and energy flows, or about the qualitative differences among sustainability conditions in different social and economic settings. Therefore, it is helpful to consider ecosystems and industrial systems alike as dynamic, open systems that operate far from equilibrium, exhibiting nonlinear and sometimes chaotic behavior.

To better understand sustainable systems, the scientific research community has increasingly pursued the field of *biocomplexity*, concerned with characterizing the interdependence of human and biophysical systems (Colwell, 1998). Interdisciplinary research teams are studying the links among industrial systems (energy, transportation, manufacturing, food production), societal systems (urbanization, mobility, communication,) and natural systems (soil, atmospheric, aquatic, biotic), including the flows of information, wealth, materials, energy, labor, and waste. The complexity, dynamics, and nonlinear nature of these interdependent systems imply that the notion of "sustainability" as a steady-state equilibrium is not realistic. Forces of change, such as technological, geopolitical, or climatic shifts will inevitably disrupt the cycles of material and energy flows. Therefore, achieving sustainability will arguably require the development of resilient, adaptive industrial and societal systems that mirror the dynamic attributes of ecological systems.

The concept of *resilience* has emerged as a critical characteristic of complex, dynamic systems in a range of disciplines including economics (Arthur, 1999), ecology (Folke et al. 2002), pedology (Lal, 1994), psychology (Bonnano, 2004), sociology (Adger, 2000), risk management (Starr et al. 2003), and network theory (Calloway et al. 2000). Resilience can be defined as *the capacity of a system to tolerate disturbances while retaining its structure and function* (Fiksel, 2003). More specifically, in the business context, we define enterprise resilience as the *capacity for an enterprise to survive, adapt, and grow in the face of turbulent change*. Enterprises need to grow, just as natural organisms do, and the concept of a static, no-growth enterprise is absurd in the business world. The real challenge, as companies like DuPont and General Motors have discovered, is to increase shareholder value without increasing material throughput. Faced with a dynamic and unpredictable business environment, management theorists are increasingly identifying the need for resilience (Hamel & Valikangas, 2003).

Engineering research has emphasized resilience or robustness as recovery from perturbations, but ecological resilience also emphasizes adaptive capacity, which may lead to new equilibria (Carpenter et al. 2001). Resilient systems, including biological and socioeconomic entities, are able to survive, adapt, and grow in the face of uncertainty and unforeseen disruptions. Arguably, the sustainability of living systems—including humans—within the changing Earth system will depend on their resilience. Traditional systems-engineering practices have tried to anticipate and resist disruptions, but may be vulnerable to unforeseen factors. An alternative is to design systems with *inherent* resilience by taking advantage of fundamental properties such as diversity, efficiency, adaptability, and cohesion (Fiksel, 2003). This approach is illustrated in the field of *green engineering*, which seeks to design products and processes with *intrinsic* characteristics that reduce or eliminate their hazardous effects (Anastas & Zimmerman, 2003).

The U.S. Environmental Protection Agency's (EPA) Office of Research and Development is now embracing a systems view of environmental progress. Its draft Sustainability Research Strategy proposes a new scientific framework for a more systematic and holistic approach to environmental protection that considers the complex nature of environmental issues and the welfare of future generations. The EPA has come to understand that designing sustainable systems encompasses several important challenges (Inside Green Business, 2006):

- Addressing multiple scales over time and space.
- Capturing system dynamics and points of leverage or control.
- Representing an appropriate level of complexity
- Managing variability and uncertainty.
- Capturing stakeholder perspectives in various domains.
- Understanding system resilience relative to foreseen and unforeseen stressors.

According to the EPA, a systems view can inform research prioritization in technology, decision-support tools, and collaborative decision-making, which in turn will enable more effective movement toward sustainability.

Integrated Approaches to Systems Modeling and Management

As the need for a systems approach becomes more apparent, the deficiencies of existing "reductionist" models are also revealed. Integrated assessment of sustainable systems cannot be accomplished by simply linking together a collection of domain-specific models. To assess the higher-order interactions among interdependent systems requires new tools to capture the emergent behaviors and dynamic relationships that characterize complex, adaptive systems. Development of such tools has been initiated by a number of multidisciplinary groups worldwide. The following examples illustrate the range of current approaches for modeling and management of complex economic, ecological, and social systems:

- *Biocomplexity in large lake systems:* A multidisciplinary research team at The Ohio State University (OSU) is investigating the complex interactions among biological, physical, and human components of large lake ecosystems (OSU, 2004). Figure 1 illustrates some of these interactions. While a large lake provides amenities, or ecological services, that support economic growth, such growth can degrade these amenities. This team of biologists, ecologists, physicists, economists, geographers, and others is attempting to model the patterns of socio-economic activity, and the potential impacts of policies to protect natural amenities, in the Lake Erie region. Beginning with simple equilibrium models, the project is investigating increasingly sophisticated techniques, including agent-based simulation.

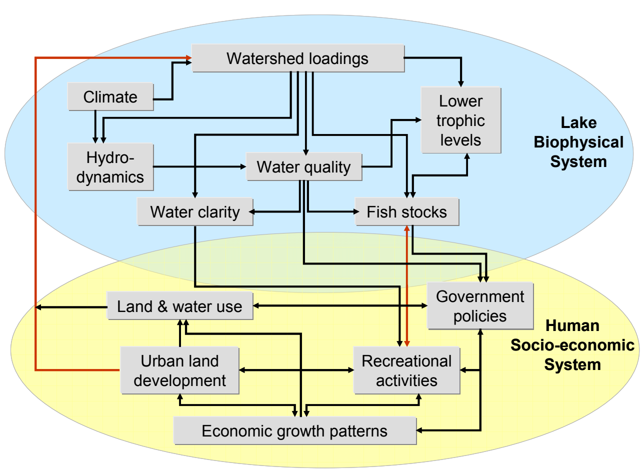

Figure 1 Modeling of coupled parameters in a lake system.

- *System dynamics modeling:* System dynamics was first developed in the 1960s and has evolved into a widespread approach for modeling dynamic, non-linear systems. The Millennium Institute has applied system dynamics to develop the Threshold 21 (T21) model, which combines proven economic-sector models into an integrated framework (Sterman, 2000). The approach uses differential equations to represent changes in stocks and flows, and considers nonlinearity, feedback, and delays. Customized T21 models have been created at a national scale for the United States and Italy, for less-developed countries (Bangladesh, Malawi), and at a regional level in Africa and Indonesia. A typical high-level model structure is illustrated in Figure 2.

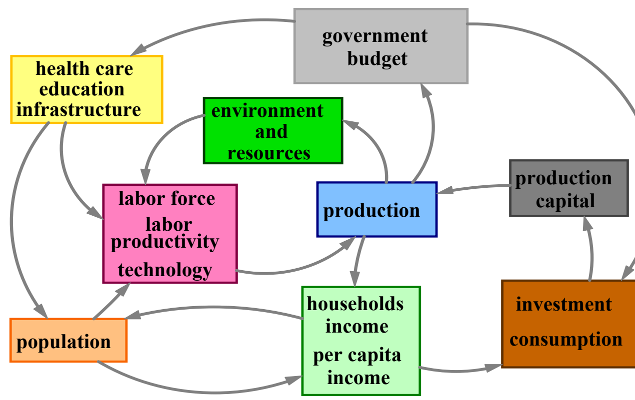

Figure 2 Structure and feedback loops in Threshold 21 system dynamics model.

- *Ecological engineering and restoration:* Recent catastrophic events, such as the Indian Ocean tsunami and Hurricane Katrina, have highlighted the vulnerability of coastal areas. Scholars have argued that ecologically restored landscapes could have mitigated these disasters and would be more cost-effective and sustainable than traditional engineering solutions such as dams and levees (Mitsch & Jørgensen, 2004). For example, ecological engineering at a watershed-scale in the Mississippi River Basin would not only improve resilience to flooding and enhance ecological processes, but also would significantly reduce the nitrogen load that causes a hypoxic zone in the Gulf of Mexico. Similarly, the restoration of the Mesopotamian marshes in Iraq, destroyed by the Saddam Hussein regime, requires a systems approach to enable sustainable socio-economic recovery (Richardson et al. 2005).
- *Climate impacts on urban infrastructure:* Urban infrastructure systems are long-lived investments with significant impacts on sustainability, and

are very sensitive to climate and resource demands. Therefore, policymakers need to understand the potential impacts of climate change on infrastructure. Under a grant from the EPA, a group of researchers has used a scenario-based dynamic modeling framework to assess impacts of climate, socioeconomic, and technological changes on the future evolution of urban-infrastructure systems in metropolitan Boston (Ruth & Lin, 2005). Detailed models and indicators were developed for four major systems: transportation, water resources, energy use, and public health.

- *Thermodynamic Life Cycle Analysis (LCA):* A recent approach developed at OSU complements traditional LCA by modeling an industrial system as a network of energy flows governed by the laws of thermodynamics (Ukidwe & Bakshi, 2004, 2005). Traditional LCA methods are mainly "output-side" in that they focus on emissions and their impacts. In contrast, Thermodynamic LCA is an "input-side" approach, relying mainly on data about consumption of natural resources expressed in terms of available energy (*exergy*). Thus it is particularly useful in the early stages of technology innovation. It accounts for the contribution of ecosystem goods and services to industrial activity, thus quantifying the preservation of natural capital. As shown in Figure 3, the method has been applied to 488 sectors of the U.S. economy, demonstrating a reduction in natural-capital intensity from extraction to manufacturing to service industries.

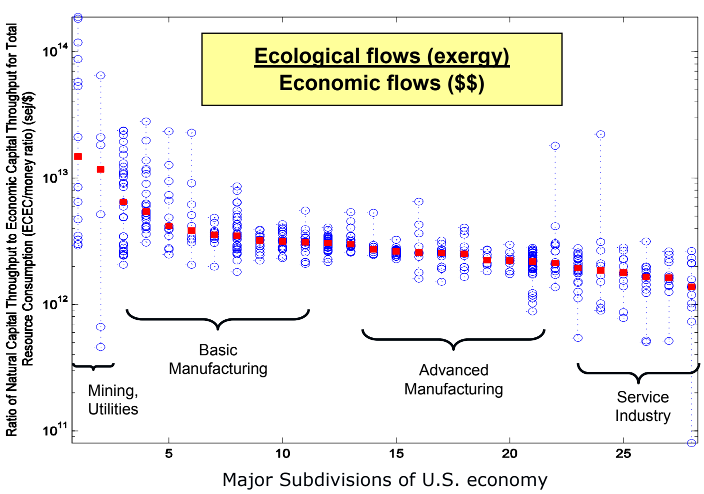

Figure 3 Sector ratios of natural capital (exergy) to economic throughput

- *Protection of ecosystem services:* The Millennium Ecosystem Assessment is an ongoing, worldwide effort to evaluate the consequences of ecosystem change for human well being and to explore plausible ecological futures (Millennium Ecosystem Assessment, 2006). Ecosystem services provide food and other resources, regulate environmental processes, and fulfill human cultural needs. However, decreasing biodiversity, resource depletion, and other changes due to anthropogenic forces are degrading many of these ecosystem services. Strategies for improving ecological resilience include broadening knowledge sources, such as local ecological knowledge; increasing human ability to cope with change and uncertainty; introducing adaptive management practices that integrate monitoring, adaptation, and mitigation; and building practical, social, and scientific networks (Carpenter et al. 2006).

The above examples typify the worldwide groundswell of cross-disciplinary work in sustainability science and engineering. One international group, called the Resilience Alliance, has proposed a new model to characterize the evolution of complex, non-linear systems in terms of an "adaptive cycle" of growth, crisis, transformation, and renewal; thus, mature forests are periodically destroyed by fire or vermin, and then regenerate (Gunderson & Holling, 2002). Similarly, industrial systems are vulnerable to disruptions such as accidents or economic crises, but after a period of "creative destruction," they enter a new, more resilient growth phase (Hart & Milstein, 1999). Analogous models are being developed in the study of resilience in psychological, social, and cultural systems (Hurst, 1995). While they may provide fresh insights, it is unlikely that any of this new generation of biocomplexity models will achieve a rigorous and scientifically defensible *predictive* capability. Certainty has become an anachronism, and decision making must occur in the context of a wide spectrum of changing possibilities.

Applications to Energy and Mobility Systems

Energy and mobility—power and movement—are essential for human society. However, the global economy faces unprecedented challenges in meeting growing energy and mobility demands, due to the clash between economic development and resource limitations. Continued economic expansion raises questions about how existing systems can meet today's needs without compromising the well being of future generations. In short, how can energy and mobility services be sustainable?

The energy and transportation industries are exploring a broad portfolio of alternative technologies; yet we have only a vague understanding of the future social, economic, and environmental conditions (e.g., demographic patterns) that will influence energy and mobility supply and demand. These conditions will vary enormously across developing and developed nations, urban and rural settings, and different geographies. Nor do we understand the full ramifications of technology choices upon economic vitality, ecological integrity, or community well being. Therefore, technology development must be accompanied by integrated assessment of the feasibility, eco-efficiency, sustainability, and resilience of these new technologies, providing a sound scientific basis for public policy formulation and research priority setting.

The following are examples of leading-edge efforts to incorporate sustainable systems thinking into the design and development of new energy and mobility solutions:

- *Well-to-wheels life cycle modeling:* In response to concerns about oil dependence and greenhouse gases (GHG), new fuels such as hydrogen and biofuels are being promoted for use in advanced hybrid electric and fuel cell vehicles. Argonne has developed the GREET (**G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation) model for "well-to-wheels" analysis of life cycle energy and emission benefits (Wang, 2001). The model distinguishes two major stages—well-to-pump and pump-to-wheels—and analyzes the life cycle resource use and emissions associated with production, delivery, use, and disposition of both fuels and vehicles. Careful analysis of future technologies suggests that hybrid electric engines with hydrogen fuel cells will provide the best combination of GHG reduction and urban NO_x emissions.
- *Complexity science and sustainable mobility:* The University of Michigan's SMART (**S**ustainable **M**obility and **A**ccessibility **R**esearch and **T**ransformation) Project unites two dozen complexity-science scholars and practitioners in the search for systemic, robust high-leverage solutions to the myriad challenges posed by currently unsustainable transportation and urban development patterns (Gladwin, 2006). Interdisciplinary teams are building agent-based and system-dynamics models of the evolution of the hydrogen infrastructure, transition to use of advanced biofuels, future market penetration of hybrid vehicles, interaction of "new urbanism" and "new mobility," and evolution of human movement and access systems in the world's megacities.
- *Systems impacts of alternative fuels:* Selection among alternative fuels requires an understanding of their full implications—for example, using bio-based fuels may imply the use of agricultural pesticides. This is a challenging task due to the complexity of the supply chains, the many alternative raw materials and production pathways, uncertainties in data and models, interactions with economic factors, and the effect of social preferences. An interdisciplinary team at OSU is applying a unique statistical framework for assessing the true impacts of emerging technologies (Bakshi, 2006). It considers the full life cycle impacts at multiple scales, from an individual facility to an industrial supply chain to the global economy. This framework will be used to study alternate fuels including gasoline, ethanol, biodiesel, and hydrogen, and to understand the transitional effects of fuel switching.

While some progress is being made, the scope and complexity of sustainable energy and mobility issues remains daunting. In an integrated global economy, it is no longer possible to deconstruct the interrelationships among global energy flows, resource consumption, and regional economic activity patterns. A case in point is the worldwide response to concerns over global warming. The combined impacts of electric power generation and internal combustion engines account for a majority of today's global GHG emissions. Significant reductions are being pursued through establishment of carbon trading mechanisms and carbon emission inventory protocols. However, the most rigorous protocol yet developed does not seek to account for non-GHG effects (e.g., ecological impacts) of carbon management projects, although it does include procedures for life cycle analysis of secondary GHG effects (WRI & WBCSD, 2005).

The introduction of market-based systems—for example, cap-and-trade—may yield efficient reductions with currently available technologies, but efforts to develop alternative low-carbon technologies are severely underfunded. The financial discounting calculus of private investment is inadequate to address long-term energy-technology priorities. Instead, coordinated public investment in high-risk, exploratory research is needed, including both technological innovations for sustainable energy and mobility solutions and analytic capabilities to test their resilience at a system level. Moreover, adaptation to climate change requires serious consideration, since global warming impacts are non-linear and may manifest abruptly, with developing nations in the tropics bearing a disproportionate share of the impact. Strategic adaptation will require global cooperation, infrastructure investment, and large-scale engineering to assure the resilience of human society to ecosystem disruptions.

A Path Forward

The current lack of success in improving industrial sustainability, coupled with the challenges of biocomplexity and resilience, indicates that sustainability is a systems problem requiring collaborative solutions. Only a coordinated global effort, with participation from public, private, and nongovernmental organizations, can achieve genuine systemic change. The difficulties encountered with the Kyoto Protocol suggest that such coordination will not be easy. Indeed, global warming issues are perhaps the most tractable, since emissions dissipate in the atmosphere and do not concentrate geographically. There are a number of other pressing ecological issues—soil resilience, biodiversity, water quality, deforestation—that involve interaction of complex local and regional ecosystems. The types of models used formerly to analyze environmental impacts are too limited in scope to address these complex systems. The previous sections have identified a number of emerging approaches to these challenges.

An important research priority for the study of sustainable systems is development of modeling and decision-making approaches that support dynamic, adaptive management rather than static optimization. This requires methods for understanding the full implications of alternative choices and their relative attractiveness in terms of enhancing system resilience. Due to the complexity of coupled systems, researchers should explore the simultaneous use of multiple models that reflect different system interpretations or stakeholder perspectives. Other potentially helpful approaches include simplified analysis of complex, multi-domain models through decomposition, aggregation, or dimensionality reduction; and utilization of biophysical simulations in place of theoretical models—for example, mesocosm experiments for complex ecological systems.

A number of technical advances will likely improve the usefulness of models, including rigorous methodologies for dealing with missing and uncertain information; improved methods for interpretation of multivariate data sets and for multi-objective decision making involving trade-offs among conflicting goals; and novel modeling methods as alternatives to traditional mathematical models, e.g., agent-based models with appropriate utility functions. More generally, there is a great need for operational definitions and metrics for sustainability and resilience in economic, ecological, and societal systems.

While improving modeling techniques and establishing a rigorous science of sustainability is important, a *caveat* is in order. Excessive modeling efforts may become an excuse for delaying effective political action, leading to "paralysis by analysis" (Cohen & Howard, 2006). Progress in theory-based research needs to be balanced with exploratory policy implementation that will enrich our understanding of sustainability issues in real-world systems. Additional discussions at OSU symposium resulted in the following recommendations for encouraging broad adoption of a systems approach to sustainability:

- Foster transdisciplinary collaboration in university research by creating incentives for interdepartmental teaming on issues of social relevance.
- Improve communications to educators, government, the media, and the general public to convey the urgency of sustainability challenges.
- Develop policy-formulation tools that recognize the complex, interconnected nature of ecological and socio-economic systems, including visualization methods and appropriate metrics.
- Explore ways to introduce an awareness of ecological systems into commerce, as in the emergence of integrated energy management services and sustainable architectural practices.
- Develop mechanisms for integrated dialogue among industry, government, and academia, shifting from an adversarial to a cooperative approach.

Sustainable development in a changing global environment will require resilience at many levels, including human communities and economic enterprises. In the face of ever-increasing global complexity and volatility, it is essential to move beyond a simplistic "steady state" model of sustainability. Instead, we need to develop adaptive policies and strategies that enable societal and industrial institutions to cope with unexpected challenges, balancing their need to flourish and grow with long-term concerns about human and ecological well being. In particular, addressing the challenge of global warming will require unprecedented international cooperation in both the development of alternative technologies and adaptation to climate change impacts.

Acknowledgment

This essay is based primarily on presentations and discussions at an interdisciplinary symposium entitled: "Resilience, Biocomplexity, and Industrial Ecology: Insights for Future Energy and Mobility Systems," held at Ohio State University on March 2 and 3, 2006. The full symposium program, as well as downloads of the presentations, are available at Ohio State's Center for Resilience website, http://www.resilience.osu.edu. Partial funding was provided by the National Science Foundation, Biocomplexity in the Environment Program, under Grant ECS-0424692.

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References

Adger, W. 2000. Social and ecological resilience: are they related? *Progress in Human Geography* 24(3):347–364.

Allenby, B. 2005. *Reconstructing Earth*. Washington, DC: Island Press.

Allenby, B. & Fink, J. 2005. Toward inherently secure and resilient societies. *Science* 309(5737):1034–1036.

Anastas, P. & Zimmerman, J. 2003. Design through the 12 principles of green engineering. *Environmental Science and Technology* 37(5):94A–101A.

Arthur, W. 1999. Complexity and the economy. *Science* 284(5411):107–109.

Bakshi, B. 2006. Thermodynamic Analysis of Industrial Ecological Systems. http://www.resilience.osu.edu/BhavikBakshi.pdf. March 3, 2006.

Bertolucci, M. 2006. Sustainable Development in Theory and in Practice at Interface. http://www.resilience.osu.edu/Mike Bertolucci.pdf. March 2, 2006.

Bonanno, G. 2004. Loss, trauma, and human resilience: have we underestimated the human capacity to thrive after extremely aversive events? *American Psychologist* 59(1):20–28.

Callaway, D., Newman, M., Strogatz, S., & Watts, D. 2000. Network robustness and fragility: percolation on random graphs. *Physical Review Letters* 85(25):5468–5471.

Carpenter, S., Bennett, E., & Peterson, G. 2006. Scenarios for ecosystem services: an overview. *Ecology and Society* 11(1):29. http://www.ecologyandsociety.org/vol11/iss1/art29/ES-2005-1610.pdf.

Carpenter, S., Walker, B., Anderies, J., & Abel, N. 2001. From metaphor to measurement: Resilience of what to what? *Ecosystems* 4(8):765–781.

Cohen, M. & Howard, J. 2006. Success and its price: the institutionalization and political relevance of industrial ecology. *Journal of Industrial Ecology* 10(1–2):79–88.

Colwell, R. 1998. Balancing the biocomplexity of the planet's living systems: a twenty-first century task for science. *BioScience* 48(10):786–787.

Cullum, T. 2006. Applications to Energy and Mobilility Systems–Progress at GM. http://www.resilience.osu.edu/TerryCullum.pdf. March 2, 2006.

Davis, J. 2006. Chevron Energy Solutions. http://www.resilience.osu.edu/JimDavis.pdf. March 2, 2006.

Ehrenfeld, J. 2005. The roots of sustainability. *Sloan Management Review* 46(2):23–25.

Fiksel, J. 2003. Designing resilient, sustainable systems. *Environmental Science and Technology* 37(23):5330–5339.

Fiksel, J. 2006. A framework for sustainable materials management. *Journal of Materials* 58(8):15–22.

Folke, C., Carpenter, S., Elmquist, T., Gunderson, L., Holling, C., & Walker, B. 2002. Resilience and sustainable development: building adaptive capacity in a world of transformations. *Ambio* 31(5):437–440.

Gladwin, T. 2006. Symposium Presentation. http://www.resilience.osu.edu/SustainableSystems.html. March 3, 2006.

Gunderson, L. & C. Holling (Eds.). 2002. *Panarchy*. Washington, DC: Island Press.

Hamel, G. & Valikangas, L. 2003. The quest for resilience. *Harvard Business Review* 81(9):52–57.

Hart, S. & Milstein, M. 1999. Global sustainability and the creative destruction of industries. *Sloan Management Review* 41(1):23–33.

Inside Green Business. 2006. EPA Sustainability Chief Details Broad Transitional Challenges. http://insidegreenbusiness.com/index.php/igb/public/1121. August, 7, 2006.

Hurst, D. 1995. *Crisis and Renewal*. Cambridge, MA: Harvard Business School Press.

Lal, R. 1994. Sustainable land use systems and soil resilience. In D. Greenland & I. Szabolcs (Eds.), *Soil Resilience and Sustainable Land Use.* pp. 41–68. Wallingford: CAB International.

Millennium Ecosystem Assessment. 2006. About the Millennium Ecosystem Assessment. http://www.millenniumassessment.org/en/about.overview.aspx? August, 26, 2006.

Mitsch, W. & Jørgensen, S. 2004. *Ecological Engineering and Ecosystem Restoration*. New York: John Wiley.

Ohio State University (OSU). 2004. Federal Grant Helps Researchers Study Complex Relationships between Humans and Lake Erie. http://researchnews.osu.edu/archive/biocomp.htm. August 25, 2006.

Richardson, C., Reiss, P., Hussain, N., Alwash, A., & Pool, D. 2005. The restoration potential of the Mesopotamian marshes of Iraq. *Science* 307(5713):1307–1311.

Ruth, M. & Lin, A. 2005. Regional energy demand and adaptations to climate change: methodology and application to the State of Maryland, USA. *Energy Policy* 34(17):2820–2833.

Starr, R., Newfrock, J., & Delurey, M. 2003. Enterprise resilience: managing risk in the networked economy. *strategy+business* 30(1):1–150. http://www.strategy-business.com/press/16635507/8375.

Sterman, J. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. New York: Irwin McGraw Hill.

Ukidwe, N. & Bakshi, B. 2004. Thermodynamic accounting of ecosystem contribution to economic sectors with application to 1992 US economy. *Environmental Science and Technology* 38(18):4810–4827.

Ukidwe, N. & Bakshi, B. 2005. Flow of natural versus economic capital in industrial supply networks and its implications to sustainability. *Environmental Science and Technology* 39(24):9759–9769.

Venetoulis J., Chazan, D., & Gaudet, C. 1994. *Ecological Footprint of Nations*. San Francisco: Redefining Progress.

Wang, M. 2001. *Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies*. Report ANL/ESD/TM-163. Argonne, IL: Center for Transportation Research, Argonne National Laboratory. http://www.transportation.anl.gov/pdfs/TA/153.pdf.

World Resources Institute (WRI) & World Business Council for Sustainable Development (WBCSD). 2005. *Greenhouse Gas Protocol: The GHG Protocol for Project Accounting*. Washington, DC: World Resources Institute.

ARTICLE

Sustainability, well being, and environmental protection: perspectives and recommendations from an Environmental Protection Agency forum

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According to panelists at a recent EPA-sponsored forum, at its essence sustainability requires the simultaneous promotion of equitable economic growth, environmental protection, and social well being. Panel members, including economists, policy makers, sociologists, and business strategists, agreed that a sustainable economy should preserve its capacity to generate income, which is made possible by maintaining natural capital. However, they also noted that the limited data available leads to the conclusion that the current scale and quality of economic activity is reducing the capacity of the biosphere to sustain the economy, and is fundamentally unfair to future generations. For EPA to respond effectively, it will have to strengthen the integration of traditional physical and biological research with behavioral and economic research. It will also require institutions that support equitable access to resources and a political system that can respond to today's poor as well as providing for future generations. Several panelists noted that habit formation and consumption patterns, which often lack a clear rational economic base, can significantly shape the relationship between income and well being. This research implies that public policy directed at sustainability can and should incorporate social values not necessarily reflected in the traditional economic theory of decision making. Several recommendations which emerged from the forum focused on the need to foster high quality data on sustainability indicators, policy mechanisms that use economic incentives, and public education regarding what constitutes sustainable decision making.

KEYWORDS*:* socioeconomic factors, environmental protection, public policy, sustainable development, resource management, rights of future generations

Introduction

The United States Environmental Protection Agency's (EPA) Office of Research and Development (ORD) is currently developing a research strategy to further sustainability through advanced scientific understanding, applications of new technologies, and environmentally and economically sound public polices.[1] A central element of this strategy is better integration of ongoing traditional physical and biological research with behavioral and economic research.[2] This is particularly important as society faces difficult decisions related to simultaneously promoting in an equitable manner economic growth, environmental protection, and social well being. Toward that goal, ORD organized a forum of experts from the physical sciences, economics, and public policy to provide input into developing its sustainability research strategy. This article summarizes what we see as the most salient analysis and recommendations presented by forum panelists. The forum program appears in the Appendix.[3]

Defining Sustainability and Metrics: Panelist Views

Herman Daly opened the first session with a definition of sustainability that recognizes that the biosphere, or natural capital, *sustains* the economy, which in turn supports quality of life (e.g., health, security, and the "pursuit of happiness"). He further explained that the biosphere is the total natural system of biogeochemical cycles powered by the sun.

[1] The draft Sustainability Research Strategy is available at http://www.epa.gov/sustainability. This document is being peer reviewed by EPA's Science Advisory Board and their final report will be published in early 2007.

[2] ORD's Economics and Decision Sciences extramural research program is described at http://es.epa.gov/ncer/science/economics/economics.html.

[3] Précis papers prepared by forum presenters, as well as a rapporteur's summary of the four panels, are available at http://www.epa.gov/sustainability/econforum.

The economy, on the other hand, is the *subsystem* dominated by transformations of matter and energy to serve human purposes. The problem, he explained, is that the current scale and quality of these transformations interfere significantly with the biosphere, reducing its capacity to sustain the economy, and are thus fundamentally unfair to future generations. This observation raises difficult questions, including what "sustaining the human economy" means: Is it a matter of achieving a given *level* of matter-energy throughput, gross domestic product (GDP), utility or welfare, total capital stock, or natural capital stock? Or does it mean sustaining a given *rate of growth* of any one of these indicators? Sustaining a rate of growth is vastly different from sustaining a certain level of growth. While panelists generally agreed on the need to sustain the biosphere, we note that historically humans have not revealed themselves to be effective environmental stewards—as attested in Jared Diamond's (2004) compelling review of ancient and modern societies whose depletion of natural resources have led to their own destruction.[4]

Building on Daly's view, several forum panelists proposed that sustainability should incorporate *non-declining levels of ecosystem services and community welfare*, as well as distributional equity among generations. Bhavik Bakshi elaborated that a sustainable economy should preserve its capacity to generate income, which is made possible because natural capital is maintained. Geoffrey Heal noted that sustainability encompasses two equally important functions: fairly distributing economic benefits over time and limiting the negative environmental impact of economic activity. Another way to assess sustainability, according to William Pizer, is to ask whether a current action (or absence of action) leaves future generations with less desirable options than those enjoyed by the current generation.

Panelists and discussants agreed on the difficulty of defining indicators that could demonstrate the existence of sustainability. Bakshi observed that in practice the opposite has been easier, the development of metrics that signal unsustainable actions. Unfortunately, the number of environmental indicators regularly measured in the United States has been decreasing, as has the number of measurements of these indicators. As a consequence, the task of deriving either positive or negative metrics for sustainability is becoming more difficult. Anthony Janetos contended that the paucity of management systems to track changes in the environment is making the transition to sustainability ever more challenging. He further remarked that several significant indicators suggest that today's generation is not better off than previous generations, implying that our social and economic systems may have already become unsustainable. The limited available data, such as that presented in the United Nations-sponsored Millennium Ecosystem Assessment (2005), indicate that the biosphere's carrying capacity is already declining.

Social and Institutional Contexts of Decision Making for Sustainability: Panelist Views

Several panelists agreed that the traditional economic model of rational decision making does not accurately reflect actual economic behavior. As such, it has limited worth for understanding and encouraging sustainability. John Gowdy noted that individual valuation of monetary payoffs depends on the social context. Pizer expanded upon this observation, pointing out that survey and experimental evidence suggest that habit formation and relative consumption effects, which often lack a clear rational base, may significantly shape the relationship between income and well being. Gowdy, in turn, recommended that EPA research and policies should incorporate these findings by exploring the use of citizen juries and community-valuation workshops to add subjective measures of well being to cost-benefit analysis. Should this valuation research find evidence of the features of persistence, irreversibility, and non-substitutability that are embedded in the concept of sustainability, according to Pizer, EPA then may not need to develop an entirely new approach to valuation and decision making for sustainability.

Another research challenge advanced by Mark Anielski is to discover suitable weights or values to place on sustainability indicators. Lisa Wainger further suggested that consideration of the social context of decision making implies that sustainability policies should reflect socially acceptable risk levels for various ecological services. Therefore, risk-tolerance concepts should be introduced to help develop hierarchical measures of sustainability, facilitate communication, and improve decision making. Such a risk-based approach would acknowledge uncertainty and shift the focus of sustainability from a purely technical one to a consideration of collective risk tolerance.

Forum panelist Richard Howarth argued that if government agencies are to fulfill their trusteeship duties under the sustainability principle they must conserve and sustain the services provided by natural systems to ensure that future generations are justly

[4] Diamond (2004) argues that the natural system is at the center of economic growth. Rejecting the common assertion that "the environment has to be balanced against the economy," he insists that "this quote portrays environmental concerns as a luxury, views measures to solve environmental problems as incurring a net cost, and considers leaving environmental problems unsolved to be a money-saving device. This one-liner puts the truth exactly backward."

compensated for environmental degradation. This reorientation has implications for how EPA and other government agencies are organized. For example, forum participants noted the need for a more holistic regulatory focus on the circular flow of material based on the cradle-to-cradle concept advanced by William McDonough and Michael Braungart (2002) instead of the current media-focused approach that underlies EPA's current organizational structures and environmental regulations. Bryan Norton called for building institutions that support equitable access to resources and shaping the political system to both respond to today's poor and provide for future generations. To carry out this dual task, communication must reflect the interdisciplinary nature of the discourse on sustainability and create language that is more accessible to the broader public. Meghan Chapple-Brown urged EPA to create win-win outcomes for the economy and the environment by assisting firms to use sustainability as a driver for market innovation. Responding to Dinah Koehler's observation that market-driven technological development has promoted environmental degradation, Geoffrey Heal noted that government's role is to apply taxes or other interventions to internalize the negative environmental impacts of new technology. Such an outcome requires government action that extends beyond free markets. EPA can thus contribute to developing a social context receptive to sustainability, rather than relying on the optimistic assumption that individuals will promote sustainability by following an innate economic rationale.

What's An Agency to Do?

EPA has recently undertaken several activities that reflect sustainability imperatives. At the request of the agency administrator, senior EPA managers have prepared a new stewardship initiative aimed at encouraging stewardship-related activities by individuals, businesses, and government. The report *Everyday Choices: Opportunities for Environmental Stewardship* recognizes that our nation's natural resources are the common property of all Americans of this and future generations, and that collective action is needed to adequately protect these resources.[5] In this document, the senior managers describe sustainable outcomes in six resource areas relevant to EPA's mission (see Table 1). This initiative marks the first explicit statement in which EPA senior leadership has focused on sustainability outcomes for the nation. Table 1 provides an important starting point for discussion of appropriate sustainability goals and how they should be measured.

[5] Report available at http://www.epa.gov/innovation.

Table 1 Sustainability outcome measures proposed in *Everyday Choices*.

Natural Resource Systems	Sustainable Outcomes
Energy	Generate clean energy and use it efficiently.
Air	Sustain clean and healthy air.
Water	Sustain water resources of quality and availability for desired uses.
Materials	Use materials carefully and shift to environmentally preferable materials.
Land	Support ecologically sensitive land management and development.
Ecosystems	Protect and restore ecosystem functions, goods, and services.

This emphasis on achieving sustainable outcomes has profound implications for EPA. In the preface of *Everyday Choices*, current EPA administrator Steve Johnson observed a natural evolution in thinking about the environment—from pollution control, to pollution prevention, to sustainability.

In the 1970s, pollution from single sources was the obvious immediate challenge. In the following decades, pollution sources were understood to be more diverse, and regulations and public polices began to target preventing pollution rather than cleaning it up. Today, environmental stresses are increasingly global due to greater economic integration.[6]

Recommendations of Forum Participants

If EPA is to achieve major progress towards sustainability, it must recognize and carry out at least three clear mandates that we see as salient recommendations from the Forum on Sustainability, Well Being, and Environmental Protection:

Promote the collection and availability of high-quality data for sustainability indicators and the development of appropriate new indicators.[7]

Existing systems to monitor and assess environmental health are under stress. Many existing systems represent a significant weakness in our ability to measure progress toward sustainability. EPA's 2003 *Draft Report on the Environment* (RoE) provides a snapshot of the state of the environment across air,

[6] The forward-looking *RCRA 2020 Strategy* of EPA's Office of Solid Waste recognizes the unsustainable nature of managing *waste* and advocates a shift toward management of *materials*. This report is available at http://www.epa.gov/osw/vision.pdf.

[7] There is always the question of whether we will ever have all the data we need. The answer is no. But the salient issue is asking the correct questions, which in turn direct how data are collected and how environmental outcomes are measured.

water, and land systems.[8] Indicators were defined in relation to clearly stated questions, such as "what are the trends and conditions of surface waters?" The Draft RoE answers many questions about current environmental conditions. However, it also highlights the difficulties of synthesizing data collected from many different systems serving different purposes and goals.[9]

Similar difficulties are evident from the Heinz Center's 2002 *State of the Nation's Ecosystem* report.[10] Again, while this report is a major step forward in assessing the status of existing ecosystems, the underlying data crucial to guiding public policy are inadequate in many places. As a result, many questions posed in the report could not be answered because of poor data availability.

Workshop participants focused on both the problems of data gathering and the basic questions for which data are being collected. Heinz Center Vice President Anthony Janetos made it clear that concerted federal and state action is needed to ensure that existing data systems are maintained and improved. But looking ahead to measuring progress, the question remains how to define sustainability and how to translate this definition into meaningful, cost-efficient indicators. What indicators, for example, would be needed to measure progress toward achieving the sustainable outcomes defined in the EPA *Everyday Choices* report?

A clear need exists for an overall strategy along the lines defined by the National Research Council (2005) report, *Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program*. This document recommends that "[a] good strategic plan must precede the development of metrics. Such a plan includes well-articulated goals against which to measure progress and a sense of priority. Absent this context, it is difficult to select the most important measures for guiding the program." The sustainability outcomes identified in *Everyday Choices* are a start. Refining these goals will allow specific sustainability indicators to be defined. The effort to develop very specific sustainability indicators needs to be balanced by an effort to overcome the paralysis caused by sparse and poor quality data. Even small steps toward developing and adopting sustainability indicators should be considered a laudable EPA goal.

Develop and implement voluntary programs and market-oriented policies that use economic incentives to foster sustainable and equitable outcomes.

In 1999, the Organization for Economic Cooperation and Development (OECD) identified 42 voluntary environmental initiatives in the United States with an estimated 13,000 participants. The vast majority of these (33) are public voluntary programs that were launched by EPA during the 1990s, with a large number focusing on global climate change (OECD, 2003). Other voluntary approaches in the United States include negotiated agreements, industry-initiated unilateral commitments, and state and regional voluntary initiatives (Brouhle, et al. 2005). Despite this significant number of innovative programs, EPA continues to rely on more traditional forms of environmental regulation and in particular on standards-based regulation. Given the global nature of a growing set of environmental problems, from transboundary pollutants to climate change, EPA will increasingly seek to pursue voluntary agreements precisely because they do not involve extraterritorial jurisdiction.

Like voluntary agreements, support for market-oriented policies such as economic incentives has grown in the last fifteen years. Crafted as an alternative to traditional command-and-control legislation, economic inducements reward or punish behavior, usually through price mechanisms such as penalties or fines. However, such policies do not specify how a facility or firm must achieve reductions in its environmental impact. The most widely recognized technique is tradable emissions permits such as the highly successful cap-and-trade program for sulfur dioxide. Because such measures allow facilities and firms more flexibility, market-based incentives generally appear to reduce the cost of pollution abatement while generating environmental improvements (see, e.g., Harrington et al. 2004). While in theory this kind of steering may impose additional costs on firms beyond what is required to achieve compliance, in practice governments have either given away permits without charge (rather than auctioning them off) or returned revenues from effluent taxes to firms (Oates, 2006).

The growing public and political support for market-oriented policies in the context of the forces of globalization means that the achievement of sustainable outcomes, based upon metrics as described above, will require more flexible policy tools. To date, there is no clear consensus that market-oriented policies will erode the competitive position of the United States, due in part to the finding that pollution abatement costs are generally less significant than the material and labor costs associated with production

[8] Report available at http://www.epa.gov/indicators/roe/index.htm.

[9] The public report is accompanied by an extensive technical report that focuses on the quality and quantity of data used in the RoE. The technical report highlights the significant underlying research needed to ensure an adequate database for environmental monitoring.

[10] Report available at http://www.heinzctr.org/ecosystems/index.shtml.

(Palmer et al. 1995; Greenstone, 2002). Thus, while future research will be required to illuminate the strengths and weaknesses of these approaches, the benefits of greater flexibility will prove invaluable in our pursuit of sustainable development.

Use education and outreach to inform and motivate, creating the social context for sustainable decision making by consumers, investors, businesses, and all levels of government.

Countless government and business decisions are made every day, affecting all aspects of sustainable resource use. For instance, business decisions regarding material use and industrial processes affect energy and water use, waste management, and human health. These highly decentralized decisions are influenced by regulations such as the Clean Water Act that control the most obvious pollution releases and ensure multiple uses of natural resources. Most federal environmental laws are delegated to the states and to Native American tribes for implementation. Decisions at state and local levels affect urban development, land use, and provision of public services. What happens at subnational levels is thus an important yardstick for measuring progress on sustainability.

How can EPA best use its resources to motivate business to consider goals of sustainable outcomes and to help states and local communities achieve their sustainability objectives? Looking ahead, it is clear that EPA must have the technical, monitoring, and analytic capability to aid decision makers in government and the private sector to act in ways that foster sustainable outcomes. EPA's Environmental Economics Research Strategy (EERS) identifies and prioritizes research that strengthens the scientific foundation for understanding how firms and individuals make decisions, based both upon the traditional economic rational actor paradigm and upon newer behavioral economics frameworks.[11]

From a scientific perspective, EPA research has evolved to reflect the new roles and responsibilities that Congress recognized in 1998:

> While acknowledging the continuing need for science and engineering in national security, health, and the economy, the challenges we face today cause us to propose that the scientific and engineering enterprise ought to move toward center stage in a fourth role; *that of helping society make good decisions*. We believe this role for science will take on increasing importance, particularly as we face difficult decisions related to the environment [emphasis added] (United States House of Representatives, 1998).

From a regulatory and policy perspective, EPA has relied upon four approaches to achieving environmental outcomes: endorsing, facilitating, partnering, and mandating:[12]

- *Endorsing* encompasses polices that reward or encourage sustainable behaviors, such as EPA's Energy Star and Design for the Environment.
- *Facilitating* involves activities that provide information, funding, or incentives to advance sustainable behavior. These initiatives include a suite of EPA programs on consumer information, energy and water use, and industry programs such as Performance Track, as well as EPA's newest initiative on stewardship.
- *Partnering* includes a host of programs around collaborative problem solving and voluntary programs such as EPA's Climate Partnerships.
- *Mandating* relates to policy or regulations such as the National Environmental Policy Act, the Clean Air Act, and Clean Water Act, as well as presidential executive orders.

The extent to which EPA is innovative and effective in using these four approaches—actions that influence decision makers in business and government—may well determine the nature and degree of sustainability in 2020.

Postscript

Since the December 2005 forum, ORD has moved forward with its Sustainability Research Strategy and is beginning to integrate sustainability objectives into the EERS and other existing ORD research programs. This integration will be reflected in future proposal solicitation topics. More broadly, EPA is continuing to advance its newly defined stewardship agenda and is working to better define and measure sustainable outcomes. The agency has made stewardship and sustainability a new element of Goal V ("Enhance Society's Capacity for Sustainability through Science and Research") of its draft 2007-2011 Strategic Plan, calling for "conducting leading-edge, sound scientific research on pollution prevention, new technology development, socioeconomic, sustainable systems, and decision-making tools."

[11] EERS is available at http://yosemite.epa.gov/ee/epa/eed.nsf/webpages/EEResearchStrategy.html.

[12] This taxonomy is adopted from Ward (2004).

Authors' Note

The authors are solely responsible for the contents of this paper which does not represent EPA policy.

References

Brouhle, K., Griffiths, C., & Wolverton, A. 2005. The use of voluntary approaches for environmental policymaking in the U.S. In E. Croci (Ed.), *The Handbook of Environmental Voluntary Agreements*. pp. 107–134. New York: Springer.

Diamond, J. 2004. *Collapse: How Societies Choose to Fail or Succeed*. New York: Viking.

Greenstone, M. 2002. The impacts of environmental regulations on industrial activity: evidence from the 1970 and 1977 Clean Air Act Amendments and the Census of Manufacturers. *Journal of Political Economy* 110(6):1175–1219.

Harrington, W., R. Morgenstern, & T. Sterner (Eds.). 2004. *Choosing Environmental Policy, Comparing Instruments and Outcomes in the United States and Europe*. Washington, DC: Resources for the Future Press.

McDonough, W. & Braungart, M. 2002. *Cradle to Cradle: Remaking the Way We Make Things*, New York: North Point Press.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: General Synthesis.* Washington, DC: Island Press.

National Research Council. Committee on Metrics for Global Change Research. 2005. *Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program.* Washington, DC: National Academies Press.

Oates, W. (Ed.). 2006. *The RFF Reader in Environmental and Resource Policy*. Washington, DC: Resources for the Future Press.

Organization for Economic Cooperation and Development (OECD). 2003. *Voluntary Approaches for Environmental Policy: Effectiveness, Efficiency, and Usage in Policy Mixes.* Paris: OECD.

Palmer, K., Oates, W., & Portney, P. 1995. Tightening environmental standards: the benefit-cost or the no-cost paradigm? *Journal of Economic Perspectives* 9(4):119–132.

United States House of Representatives. Committee on Science. 1998. *Unlocking Our Future: Towards A New National Science Policy*. Washington, DC: Government Printing Office. http://www.house.gov/science/science_policy_ report.htm.

Ward, H. 2004. *Public Sector Roles in Strengthening Corporate Social Responsibility: Taking Stock*. Washington, DC: The World Bank.

Appendix: Forum Program and Discussion Points

Panel 1: Basis

The panel discussed the following questions:

- ✧ Is intergenerational equity a reasonable definition of sustainability? Conceptually and operationally, how do you conceive and define intergenerational equity (e.g., as constant or non-declining utility, GDP, throughput, human-made capital, natural capital, total capital)?
- ✧ How does concern for sustainability comport with the claim that each generation is generally better off than those that preceded them? Is this claim historically true? If so, over what time period, and is it likely to remain true?
- ✧ How does sustainability relate to environmental protection?

Moderator: Herman Daly, Professor of Public Affairs, University of Maryland

Panelists: Anthony Janetos, Vice President, The Heinz Center
Geoffrey Heal, Professor of Public Policy and Business Responsibility, Columbia University
Bryan Norton, Professor of Philosophy, Georgia Institute of Technology

Panel 2: Measurement

Questions considered by the panel included:

- ✧ What frameworks for sustainable development indicators (e.g., national accounts, material flows) are likely to be most useful for decision makers?
- ✧ What are the roles, strengths, and weaknesses of biophysical, economic, and social indicators related to sustainable development?
- ✧ Are there assets that are non-substitutable, and how should these affect measurement?
- ✧ Will aggregate sustainable development indicators be useful for environmental agencies, given that environment is simply part of the sustainable development puzzle?

Moderator: Kirk Hamilton, Lead Environmental Economist, The World Bank

Panelists: Mark Anielski, Independent Consultant
Bhavik Bakshi, Professor of Chemical and Biomolecular Engineering, Ohio State University
Joy Hecht, Independent Consultant
Lisa Wainger, Research Scientist, University of Maryland

Panel 3: Policy Options

The discussion centered on the following questions:

- ✧ What do we mean by “sustainability policy”? How is it different from environmental protection policy?
- ✧ What tools do we need to use to promote sustainability?
- ✧ How should EPA work with other agencies to affect their rules and regulations, which, although not explicitly environmental, affect corporate behavior and the flow of resources through the economy?
- ✧ Should EPA try to influence consumer preferences?

Moderator: Jay Benforado, Director, National Center for Environmental Innovation, U.S. EPA

Panelists: Richard Howarth, Professor of Environmental Studies, Dartmouth College
Meghan Chapple-Brown, Senior Advisor, SustainAbility
Bryan Norton, Professor of Philosophy, Georgia Institute of Technology

Panel 4: Policy Assessment

The overarching question is:

- ✧ Does the adoption of sustainability as a major policy objective suggest the need for changes in the assessment process for EPA?

Moderator: Tom Tietenberg, Professor of Economics, Colby College

Panelists: John Gowdy, Professor of Economics, Rensselaer Polytechnic Institute
Richard Howarth, Professor of Environmental Studies, Dartmouth College
William Pizer, Fellow, Resources for the Future
Michael Toman, Professor of International Relations, Johns Hopkins University

INTRODUCTION

Human response to environmental decline at the forest frontier

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Tropical landscapes with fragmented habitats and increasing levels of human use still harbor hundreds of globally threatened species that cannot survive anywhere else (Meyers et al. 2000). Ecosystem services in natural areas are also especially important for provisioning and protecting impoverished people, and have been undermined through deforestation, land degradation, and pollution. As natural assets are depleted, poverty reduction becomes more costly, with less protein from hunting and fishing and increased incidences of flooding and waterborne diseases affecting the most vulnerable communities (Millennium Assessment, 2005). Many natural areas are reaching their limits in terms of their longstanding capacity to serve as a safety net for the rural poor during periods of economic and political transformation (Pattanayak & Sills, 2001).

Considerable deforestation in tropical developing countries occurs as an unintended consequence of rural development policies that enable both rich and poor to degrade the environment as part of a process of building individual assets, only to leave the remaining landscapes less capable of supporting those who remain (Chomitz, 2006). Neither government agencies nor forest dwellers' regimes have adequate governance tools or resources to manage the vastly increased incentives for short-term profiteering in frontier regions that are experiencing agricultural expansion, road construction, and in-migration. The two papers in this forum describe how human behavioral response to changing environmental conditions at the forest frontier sets up further unintended consequences that can be understood with research. Both papers also highlight that these insights will need to be matched by a science that is only in its infancy: the ability to evaluate the causal effectiveness of policy responses (Ferraro & Pattanayak, 2006).

Naughton-Treves and colleagues find that in Ecuador and Peru protected areas occupy twice the area that they did a quarter century ago, but with increasingly complex arrangements to accommodate the thousands of people living inside their boundaries. The expansion of protected areas was often justified by the need to safeguard rare and vulnerable ecosystems, despite higher human population densities. A number of these expanded parks, some established with protections consistent with IUCN categories I or II, now include significant human populations, and this has created management regimes that are incongruous with the actual patterns of use.

In these situations, park managers have responded in some cases by adjusting the boundaries to exclude communities that rejected the enforcement of regulations, while in other cases they have worked to establish internal zoning for community use of resources. Internal zoning often has tenuous legitimacy and lacks mechanisms for observing, enforcing, or adjudicating related rules. Though the processes for making internal zones have become more participatory and transparent, the legal status of the parks means that property rights over extractive uses within the established zones remains uncertain.

Zoning as a response to the changing environmental conditions of expansive parks creates contradictory incentives and sets the stage for future conflict. Extensive areas cleared of forest within the protected areas of Indonesia, for example, inhibit agricultural use because their legal status impedes access to credit (Fay & Michon, 2005). The removal of protected status, in contrast, creates perverse incentives for further speculation in the conversion of public or communal lands. The robustness of internal zoning for parks and extractive reserves usually depends on the opportunity cost of more intensive uses and the strength of indigenous governance institutions. In some cases, growing access to markets and declining social cohesion spurred by external mining, forestry, or agricultural interests overwhelms internal zoning rules (Pinto da Silva, 2004). In other places, remoteness, community legal usage rights, and indigenous institutions are factors that can shore up the longevity of internal zoning rules (Nepstad et al. 2006).

This article by the group led by Naughton-Treves helps us to understand how the goal of slowing forest conversion, through the expansion of protected areas, and the postponement of legal usage rights inside them has created conditions for a human behavioral response—namely zoning—that will require a further evolution in the management institutions operating in protected areas. The authors recommend approaches providing formal contractual agreements between park authorities and resident communities in the form of co-management or compensated use-restrictions. Soon, park-management agencies may have financial mechanisms allowing them to pay communities for the carbon-storage value of avoided deforestation. However, the effectiveness of such institutions at reconciling forest-conversion control with economic opportunities for the mostly poor communities remains uncertain. Are park managers more effective implementers of co-management contracts, or are local governments, all other factors being equal? Greater clarity about the nature of the sustainability problem is necessary but not sufficient to allow prescription of policy responses likely to be more effective Understanding effectiveness will require tests of these instruments, controlling for varying market access, under different economic returns for logging, hunting, mining, and agricultural conversion.

In the same frontier regions, Pattanayak and his colleagues show that environmental change is a probable precursor to human behavior that will have consequential, but poorly understood, human-health effects. Degraded natural environments, with stagnant water pools, higher acidity, increased edge environments of patchy secondary growth, and greater in-migration are all likely to be linked to a resurgence of malaria, compounded by linked cascading effects of climate change and human interaction with sensitive environments. Recent scientific studies have identified independent causal links between road construction, changed human behavior, and malaria in Peru (Vittor et al. 2006) and diarrheal disease in Ecuador (Eisenberg et al. 2006).

The proposed research agenda on deforestation and human health articulates one of the chief priorities emerging from the Millennium Ecosystem Assessment:

> At present, most ecosystem services are not marketed. The resulting lack of information about prices that reflect social value is an impediment to design and implementation of economic policy instruments. The gap is particularly acute for "regulating services," such as disease and flood regulation and climate control, which are rarely priced, yet have strong effects (Carpenter et al. 2006).

Yet in the remote areas of the rural tropics, the road-development projects that these two papers contend are causally linked with greater in-migration pressure on parks and risks to human health, are usually popular with local populations. Road development is both an endogenous response to forest clearing and agricultural intensification, as well as an exogenous cause of it (Reis & Weinhold, 2004). Both theory and empirical evidence give reason to believe that some road development could improve market access for areas of intensive production, decreasing pressure on forests and bringing rural people access to health services. However, design principles for poverty-reducing roads and effective frontier-governance institutions remain almost entirely in the realm of speculative policy debate. Even as natural experiments proliferate regarding innovation in road building and frontier governance, they have not been pursued using research methodologies that adequately compare outcomes while controlling for confounding causal factors.

The science on human-environment dynamics at the forest edge continues to lag behind the emergence of new drivers of land-use change, such as the production of biofuels. The rationale for investment in controlled policy experiments can seem fragile compared to the need for direct action to prevent irreversible environmental damage. The two articles that comprise this forum implicitly caution, however, that the behavioral response to underachieving conservation action might be to reduce support for this action from its ostensible beneficiaries. This is a recipe for a continuing policy lag that delays even further the comprehensive incorporation of the total cost of biodiversity and ecosystem service loss in the prices of goods (e.g., soybeans, minerals, timber, bushmeat) that are produced at the forest edge.

The prevailing knowledge gaps on the monetized value of services that would allow for them to be incorporated in prices and help to pay for maintaining parks and controlling emergent diseases are not even the most glaring problem. The information deficiency is even greater regarding the costs of constructing the policy institutions that might implement common property regimes or economic instruments in different contexts. These institutions are unlikely to evolve out of political demands for an unrealized public good (Hoff & Stiglitz, 2001). It will be necessary to induce policy experiments and to take advantage of these opportunities to incorporate the scientific evaluation of policy effectiveness for the institutions that are developed.

Scientific insights about the places where the greatest environmental costs (and human welfare losses) might be avoided has too frequently been misperceived as knowledge about which policy interventions are effective in the extremely varied contexts where these losses can occur. This forum demonstrates the behavioral consequences that can occur when protected areas are expanded to slow deforestation and highlights a need to better understand the behavioral changes that deforestation, infrastructure development, and malaria emergence prompt in tropical areas. Facilitation of this awareness will require the integration of rigorous social and ecological science in an interdisciplinary context. This work should be aimed at understanding the opportunity costs of economic drivers, such as soybean expansion, logging, mining, hunting, and wildlife trade, in order to scale the countervailing incentives that are incorporated into common property institutions or economic instruments. To get ahead of the curve of worsening environmental degradation and the poverty traps that occur at the forest edge requires special attention to the scientific evaluation of policies that create incentives for environmental stewardship in the varied contexts of the tropical forest frontier.

References

Carpenter, S. DeFries, R., Dietz, T., Mooney, H., Polasky, S., Reid, W., & Scholes, R. 2006. Millennium Ecosystem Assessment: research needs. *Science* 314(5797):257–258.

Chomitz, K. 2006. *At Loggerheads? Agricultural Expansion, Poverty Reduction, and Environment in the Tropical Forests*. Washington, DC: World Bank.

Eisenberg, J., Cevallos, W., Ponce, K., Levy, K., Bates, S., Scott, J., Hubbard, A., Vieira, N., Endara, P., Espinel, M., Trueba, G., Riley, L., & Trostle, J. 2006. Environmental change and infectious disease: how new roads affect the transmission of diarrheal pathogens in rural Ecuador. *Proceedings of the National Academy of Sciences* (in press).

Fay, C. & Michon, G. 2005. Redressing forestry hegemony: when a forestry regulatory framework is best replaced by an agrarian one. *Forest, Trees and Livelihoods* 15(20):193–209.

Ferraro, P. & Pattanayak, S. 2006. Money for nothing? A call for empirical evaluation of biodiversity conservation investments. *PLOS Biology* 4(4):e105.

Hoff, K. & Stiglitz, J. 2001. Modern economic theory and development. In G. Meier & J. Stiglitz (Eds.), *Frontiers of Development Economics*. pp. 389–460. Washington, DC: World Bank.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being*. Washington, DC: Island Press.

Myers, N., Mittermeier, R., Mittermeier, C., da Fonseca, G., & Kent, J. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403(6772):853–58.

Nepstad, D., Schwartzmann, S., Bamberger, B., Santilli, M., Ray, D., Schlesinger, P., Lefebvre, P., Alencar, A., Prinz, E., Fiske, G., & Rolla, A. 2006. Inhibition of Amazon deforestation and fire by parks and indigenous lands. *Conservation Biology* 20(1):65–73.

Pattanayak, S. & Sills, E. 2001. Do tropical forests provide natural insurance? The microeconomics of non-timber forest products collection in the Brazilian Amazon. *Land Economics* 77(4):595–612.

Pinto da Silva, P. 2004. From common property to co-management: lessons from Brazil's first maritime extractive reserve. *Marine Policy* 28(5):419–428.

Reis, E. & Weinhold, D. 2004. *Land Use and Transportation Costs in the Brazilian Amazon.* Agricultural and Applied Economics Staff Paper Series No. 467. Madison: University of Wisconsin.

Vittor, A., Gilman, R., Tielsch, J., Glass, G., Shields, T., Lozano, W., Pinedo-Cancino, V., & Patz, J. 2006. The effect of deforestation on the human-biting rate of Anopheles darlingi, the primary vector of Falciparum malaria in the Peruvian Amazon. *American Journal of Tropical Medicine and Hygiene* 74(1):3–11.

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ARTICLE

Expanding protected areas and incorporating human resource use: a study of 15 forest parks in Ecuador and Peru

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[8] COEX: Sharing the Land with Wildlife, Inc., Madison, WI USA

Data from legal records, management plans, and interviews with 63 local experts reveal the substantial expansion of 15 protected areas (PAs) of forest in Ecuador and Peru during the last two decades. Combining results for these PAs, the area under protection increased by over half, from 5,760,814 to 8,972,896 ha, with the Amazonian PAs adding the greatest expanse. Most of this expanded land was legally designated for strict protection; however, in practice, human resource use and settlement are widespread. Hunting is the most common resource use, followed by logging and livestock grazing. Mining and petroleum extraction also occur in four of the 15 PAs. Together these activities on average affect approximately 30% of the area within eight Peruvian PAs and approximately 45% of the area of seven Ecuadorian PAs, far exceeding previous deforestation estimates. By expanding these PAs, Ecuadorian and Peruvian conservationists have significantly improved the coverage of key ecosystems and endangered habitats. However, they now face the daunting task of managing larger, more complex protected areas that *de facto* include thousands of local people. Conservation agencies in both countries are turning toward land-use zoning within PAs to integrate resource use with biodiversity conservation.

KEYWORDS: protected areas, resource availability, parks, forestry, environmental management, human settlements, logging, habitat improvement, ecosystem management, zoning, land use

Introduction

Over the past 25 years, the area of land under legal protection worldwide has increased exponentially, particularly in developing countries where biodiversity is greatest (IUCN, 2004). Concurrently, the mission of parks and reserves has also expanded significantly. By global mandates, protected areas (PAs) are now supposed to do far more than conserve biological diversity; they are charged with improving human well being, guarding local security, and providing economic benefits across multiple scales (Naughton-Treves et al. 2005). Some analysts fear that despite the recent emphasis on human welfare and poverty reduction the expansion of PAs imposes high social costs by limiting local access to land and resources (Ghimire & Pimbert, 1997; Geisler & De Sousa, 2000). Other experts are concerned that the increasingly broad goals for PAs jeopardize their ability to protect biodiversity and overstate progress toward that objective (Locke & Dearden, 2005).

Remote sensing of deforestation provides one important measure of PA effectiveness (DeFries et al. 2005), but avoiding deforestation is not the ultimate litmus test for parks. Biodiversity can be significantly compromised by "invisible" threats such as hunting (Redford, 1992). Some critics have also interpreted reduced deforestation within a given PA relative to the surrounding area as indicating that the PA is simply displacing forest extraction elsewhere and failing to promote sustainable development (Ghimire, 1994). Given the broadened objectives for PAs, monitoring effectiveness now entails accounting for an expanded list of physical and social conditions (Chape et al. 2005) and thus requires interdisciplinary research, including remote and field-based assessments.

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Table 1 Protected areas of Ecuador and Peru included in the study.

Protected Area	Year of establishment	Size at time of establishment (ha)	Size in 2003 (ha)*	Percentage change in size from year of establishment to 2003	Number of boundary changes since establishment to 2003	Range in elevation (masl)	IUCN Category (see Table 2 for definition)
Ecuadorian Protected Areas							
Reserva Ecológica Cotocachi Cayapas	1968	204,420	234,420	15	2	300-4,939	VI
Reserva Ecológica Cayambe Coca	1970	403,000	397,667	-1	1	600-5,790	VI
Reserva Forestal Cuyabeno	1979	254,760	603,380	137	5	180-300	VI
Parque Nacional Sangay	1979	271,925	517,765	90	3	600-5,230	II
Parque Nacional Yasuní	1979	679,730	982,000	45	3	500-600	II
Parque Nacional Machalilla	1979	55,059	55,059	0	3[1]	0-838	II
Parque Nacional Podocarpus	1982	146,280	146,280	0	0	900-3,600	II
Peruvian Protected Areas							
Reserva Nacional Pacaya Samiria	1940	1,500,000	2,080,000	39	3	125-800	VI
Reserva de Biosfera Manu	1968	1,532,806	1,881,200	23	5	365- 4,000	II
Parque Nacional Bahuaja-Sonene	1977	5,500	1,091,406	247	5	220-2,700	II
Bosque de Protección Alto Mayo	1979	160,000	182,000	14	2	950-4,000	VI
Parque Nacional Río Abiseo	1983	274,520	274,520	0	1[2]	320-4,500	II
Bosque de Protección Pui Pui	1985	60,000	60,000	0	1[2]	1,750-4,500	VI
Parque Nacional Yanachaga-Chemillén	1986	122,000	122,000	0	0	800-3,800	II
Bosque de Protección San Matías-San Carlos	1987	145,818	145,818	0	0	300-2,250	VI

* Size includes land legally classified as belonging *within* the specific protected area (as well as marine area in the case of Machalilla National Park). Area in adjacent corridors, buffer zones, or reserves is not included in estimate.
[1] Areas were added to the park equivalent in size to the area excised.
[2] Boundary changes were made to correct minor cartographic error.

To move beyond the highly charged but data-poor debate, we analyze management trends and patterns of resource use in 15 forest parks and reserves in Ecuador and Peru (Table 1). We first document changes in the size of these PAs and/or in management category. We then present estimates of the extent of other extractive resource uses, including hunting, fishing, mining, and livestock grazing. Our study reveals that in Ecuador and Peru considerable land has been added to protected areas, and much of this land is legally designated for strict protection (Type II in the International Union for the Conservation of Nature (IUCN) nomenclature of management categories) (Table 2). However, in practice, the actual area free from human use is considerably smaller than formal classifications indicate. The results of interviews and participatory mapping exercises also suggest that remotely sensed deforestation offers a conservative estimate of the actual area under human use. In sum, by expanding protected areas, Ecuadorian and Peruvian conservationists have significantly improved coverage of key ecosystems and endangered habitats. They now face the daunting task of managing larger, more complex PAs that, in aggregate, include thousands of people as residents and even more as forest users.

Research Design and Methods

Peru and Ecuador are both countries of great conservation importance given their extraordinary species richness and endemism and the high threat to biodiversity posed by human activities (Myers et al. 2000). Within this region, we selected PAs that met the following criteria:

- The majority of the protected area lies at less than 3,000 meters above sea level and the dominant vegetation is closed canopy forest.
- The protected area is administered by the government and one of its major official purposes is biodiversity conservation.
- The protected area was legally established before 1991.
- The protected area covers more than 10,000 ha.

Fifteen PAs met these criteria, eight from Peru and seven from Ecuador (Table 2, Figure 1). During 2003–2004, members of our team traveled to each of these PAs and interviewed, on average, four experts per park. At each site we aimed to include 1) a local representative of the government agency managing the PA, 2) a representative of an NGO actively involved in the PA, and 3) a representative of a community organization, such as an indigenous federation, agriculturalists' union, or landholders association. In all three categories of expertise, when possible, we selected individuals with more than five years of field experience in the region. During each interview, we first explained that we were not judging the performance of individuals or organizations at a given PA, but were rather gathering data for several PAs to reveal regional trends and conditions. One of the authors of this report was always present for these interviews to ensure continuity of methods across the various sites and at some PAs experts were interviewed in groups of two or three. We then presented the expert with a poster-sized map of the PA illustrating basic physical features, PA boundaries, and administrative units. Each expert was asked to describe the history of the PA, prompted by our questions regarding initial state and change in: 1) the process of PA establishment, 2) the presence of human settlements within the PA, 3) the conflicts between local communities and PA managers, and 4) the changes in the location of PA boundaries, and/or in the conservation status of internal zones. We then asked each expert to draw the present location of resource use within the PA, including both illicit and sanctioned activities. Interviews typically lasted over two hours and we offered informants the option of remaining anonymous. We subsequently plotted each expert's drawing of resource use into a GIS file.

Table 2 The six categories of protected areas recognized by the IUCN.

Category	Description
I (a and b)	Strict nature reserve, wilderness protection area, or wilderness area managed mainly for science or wilderness protection
II	National park, managed mainly for ecosystem protection and recreation
III	National monument, managed mainly for conservation of specific natural features
IV	Habitat/species management area, managed mainly for conservation through management intervention
V	Protected landscape/seascape, managed mainly for landscape/seascape conservation or recreation
VI	Managed resource protected area, managed mainly for sustainable use of natural resources

(WDPA Consortium, 2005)

Figure 1 Map of 15 protected areas included in study, Ecuador and Peru (WDPA Consortium, 2005).

A total of 63 interviews were conducted.[1] During the process, we were aware that the information we gained was potentially subjective and imprecise (Pearce et al. 2001; Doolittle, 2003; Yamada et al. 2003). The experts were obliged to sketch their maps of resource use in a rapid manner on large-scale maps. Also, PAs varied markedly in

[1] Only two field interviews were conducted for Cuyabeno Forest Reserve in Ecuador. We were able to record park history and boundary changes, but did not calculate area or intensity of use at the Reserve.

size and prior research coverage. Our effort to compile information for 15 PAs, given a limited budget and time, prohibited us from conducting field research to corroborate the informants' estimates. However, as indicated in other published accounts, participatory mapping by experts (especially long-term local residents) offers a cost-effective, rough method to complement other means of assessing human activities (Pearce et al. 2001; Yamada et al. 2003; Bojorquez-Tapia et al. 2004; Treves et al. 2006). To test the accuracy of the participatory mapping exercise in this case, we examined interobserver variability within the PAs and tested for possible biases among experts across the PAs according to the type of organization they represented and the number of years they had been working in the area. For example, it is possible that park managers might systematically over- or underestimate the extent of human activity according to their desire to emphasize their budgetary shortfalls or successes in limiting threats. Similarly, we predicted that experts with longer histories at a site would be able to identify more uses in a larger number of areas (Yamada et al. 2003). Rather than discard any individual expert's map, we present interobserver variation and statistically assess differences associated with the expert's organization and years of experience.

We supplemented these field interviews with reviews of park-management plans, reports, press releases, legal documents, and other published and gray-literature items. While we aimed to collect the same type of data for every PA, we encountered some country-level variation in the type of information available. For example, data regarding human settlement in Ecuadorian PAs was usually available as an estimate of area settled, while in Peru numbers of residents per PA were more commonly reported. In both countries, the size and location of concessions for industrial mining and oil and natural gas extraction (or exploration) were obtained from official maps.

Results

Boundary Changes, Evictions, and Zoning

Most of the 15 PAs had dynamic histories. Twelve had changed in size or level of legal protection since their creation. On average, each PA had 2.5 boundary changes since its establishment, but three had five changes (Table 1). The total area included within these 15 PAs increased by 56%, from 5,760,814 to 8,972,896 ha (the eight Peruvian PAs grew slightly more than the seven Ecuadorian PAs—Peru: 60% from the original size, 3,800,644 to 6,091,329 ha; Ecuador: 47%, from 1,960,170 to 2,881,567 ha) (Figure 2). The Amazonian PAs had the greatest absolute growth (Peru: Manu, Bahuaja-Sonene and Pacaya-Saimiria each grew by more than 500,000 ha — Ecuador: Yasuni and Cuyabeno each grew by approximately 300,000 ha). Two Ecuadorian PAs experienced the greatest expansion relative to their original size (Sangay: 90%; Cuyabeno: 137%). Whereas several PAs had portions of their area excised or degazetted, only one of the 15 PAs had a net decrease in size (Cayambe Coca Ecological Reserve decreased by 5,000 ha) (Table 1). In Ecuador, from 1982 to 2002 more of the land added for inclusion was designated for multiple use rather than for strict protection (land designated for multiple use within the seven study PAs grew by 157,300 ha (or 86%) and strictly protected land by 129,000 ha (or 54%)) (Table 1). During the same period, the reverse was true for the eight Peruvian PAs (the area under multiple use actually shrank by 64,300 ha (-31%) and strictly protected by 306,500 ha (-67%)) (Table 1).

Explanations for boundary changes vary (Table 3), but the most frequently reported reason was to

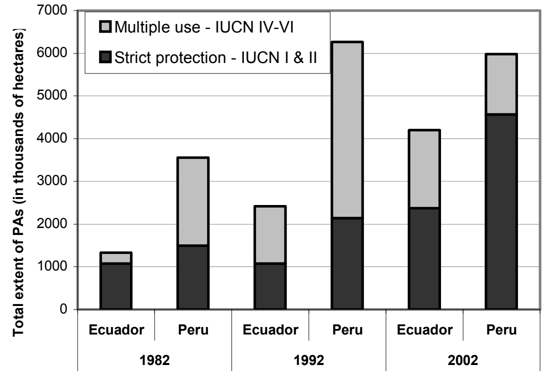

Figure 2 Area under strict protection (IUCN Categories I and II) vs. multiple use (IUCN Categories IV-VI), for 15 protected areas in Ecuador and Peru, 1982–2002.

Table 3 Historical tally and list of explanations for land additions and excisions to 15 protected areas in Ecuador and Peru, 1968–2003.

Number of changes	Explanation
14	Add land to include critical ecosystems.
9	Correcting surveying and mapping error.
9	Cede cultivated or titled land to local communities.*
2	Cede land to oil-exploration concession.
1	Add land to protect archeological treasures or monuments.

* Three of these cases involved claims by indigenous groups specifically.

expand PAs to include critical habitats or watersheds (on average, 290,000 ha were added per change: range 1,250 to 800,030 ha, standard deviation 270,060 ha). On nine occasions land was ceded to local communities (on average, 26,880 ha was ceded per change: range, 20 to 133,000 ha, standard deviation 41,550 ha). Equally frequent were boundary changes to correct cartographic or survey errors associated with original PA creation (these errors were usually only on the order of 1,000–2,000 ha per PA). On two occasions, PA boundaries were affected by oil exploration and extraction. In 1990, 133,000 ha were excised from Yasuni National Park in Ecuador to allow oil exploration and extraction (greater areas were subsequently added to the park). Similarly, 363,964 ha were removed from the original proposed area for Bahuaja-Sonene National Park in Peru, but this same area was later incorporated into the park when oil reserves proved commercially insufficient for extraction.

The following generalizations emerged from expert interviews. Typically, local communities were not consulted when the PAs were first created and this often led to subsequent conflict. However, for seven out of the 15 PAs, their official creation did not generate immediate conflict with local residents because these PAs existed for years only on paper (six were established in the 1960s and one during the 1940s). It was not until conservation rules were enforced that conflict erupted with the people dependent on natural resources in these seven areas. Beginning in the 1970s and 1980s, managers at some PAs attempted to prevent resource use by force (although in some cases use by indigenous people was allowed) (Fiallo & Naughton-Treves, 1998). Thus, small-scale farmers were evicted from Pacaya-Samiria, Rio Abiseo, and Machalilla, and Brazil nut harvesters from Pampas del Heath (Chicchón, 2000).[2] Respondents described the public outcry and occasional violent protests associated with some of these interventions. In other cases, rather than attempt to evict local people or to impose resource-use restrictions, PA boundaries were legally changed to cede land back to local citizens. For example, in the Peruvian Amazon, a portion of the transitory Tambopata Candamo Reserve Zone was excised in the year 2000 in response to residents' demands to be "liberated" from the Reserve. An interesting counterexample (also from the Peruvian Amazon) is the Manu Biosphere Reserve where communities of indigenous people and other long-term residents petitioned to have their land *included* in the PA, hoping that such action would hasten investments in sustainable development and guard the area against colonists' incursions.

All of the cases involving the ceding of PA land to communities occurred before 1993 (except for the above-described change to the Tambopata transitory reserve in Peru during 2000). Since then, a new strategy has taken hold. Now, rather than evicting people from PAs or legally excising land to communities, conservation agencies are rezoning land *within* PA boundaries to accommodate human use and thus integrate local people into the management of the PA. Park managers explained that this approach was the only realistic option given the widespread presence of human settlements and resource use in PAs. On average, approximately 12% of the area within the Ecuadorian PAs was settled (range 1–29%). Estimating the population within Peruvian PAs is confounded by the presence of two vast biosphere reserves, Manu and Pacaya-Samiria, with approximately 83,500 and 45,000 inhabitants respectively living in their buffer zones. Including these two areas, the eight Peruvian PAs we sampled were each inhabited by approximately 19,600 people (range 0–83,500). Without the two biosphere reserves, the average drops to 1,760 (range 0–5,000).

At the time of our study, 11 of the 15 PAs had official internal zoning plans, including five Peruvian PAs and six Ecuadorian PAs (a seventh Ecuadorian park had a proposed internal zoning plan, but it was not yet officially accepted). Ideally, these zoning efforts would improve relations between local residents and park authorities and allow for more management flexibility. However, according to the PA officials, only one of the eleven PAs (Bahuaja-Sonene) had at the time of this writing implemented the internal zoning plans in actual management (Landeo, 2006).

Peruvian and Ecuadorian conservation agencies are also working to promote environmentally sound development beyond the PA boundaries. With the exception of only two PAs (PuiPui in Peru and Machalilla in Ecuador), all of the sites in this study had new conservation areas added to neighboring holdings, including ethnic reserves, conservation concessions, communal reserves, protected forests, and, in the case of Peru, municipal and regional conservation areas and buffer zones. These adjacent conservation lands are sizeable,[3] covering 1,849,995 ha around six of the Ecuador PAs in our study, and 2,319,581 ha around six of the Peruvian PAs. Most of these new areas belong to IUCN categories IV–VI that allow for human uses of various intensities. In the case of Peru, officials of Instituto Nacional De

[2] Area established prior to Bahuaja-Sonene National Park.

[3] We define "adjacent conservation land" an area which legally includes environmental protection among its objectives and that shares a boundary with one of the 15 PAs examined in this project. In many instances (e.g., Yasuni National Park) adjacent conservation land includes indigenous areas.

Recursos Naturales (IRENA), the agency responsible for PA management, have also legally established large buffer zones around the eight PAs to influence land-use activities in the surrounding area in favor of environmental conservation. In practice, Peruvian PA managers have uncertain authority in these buffer zones, but the zones provide legal footing for INRENA to demand environmental impact assessments for mining and oil extraction, including analysis of potential impacts on adjacent PAs (Suárez de Freitas, 2002). In both Ecuador and Peru, there is significant overlap between indigenous territories and national parks and reserves; thus a precise comparison of area devoted to each is problematic. Some respondents were reluctant to offer data on indigenous reserves due to the highly political nature of these territorial disputes. However, the majority of our respondents stressed that indigenous territories (within and adjoining the PAs) have tremendous biodiversity conservation importance.

In sum, over the past four decades most of the PAs have expanded significantly. The concurrent expansion in the mission of the PAs has blurred the boundary between land-use activities within and outside PAs. In the 1970s and 1980s, managers at several sites attempted to implement the strict protection model of parks by evicting people and/or by excising occupied land from PAs. Managers are now more likely to accept extractive resource use in some portions of the PAs (even Type II PAs), while they also attempt to influence land use beyond PA boundaries. As a veteran Ecuadorian park guard commented:

> In the past our job was clear. We walked the park boundary and said "NO" to any use inside the park, and "OK" to anything outside the park. Now we are supposed to promote sustainable development on both sides of the boundary.

Estimating the Spatial Extent of Human Activities

We observed differences in experts' maps of extractive resource use in each protected area (Figure 3). To aid in the interpretation of the maps, we first measured the variation between experts' estimates of the percentage of area in each PA affected by the three most prominent land uses: hunting, logging, and livestock grazing. The variability was highest for estimates of logging (sd 1–31%), followed by hunting (sd 1–18%) and then livestock grazing (sd 3–9%). We then analyzed the degree of overlap between the areas of use drawn by different experts who were reporting on the same PA. We found that the experts' estimates regarding the location of resource use for each PA differed by 30% for logging (i.e., there was a 70% overlap between experts' delineation of logging areas), 23% for hunting, and 11% for livestock grazing (n=45 interobserver differences for logging and hunting, n=42 for livestock grazing). The size of the differences between estimates increased with the size of the PA, except in the case of Ecuador's relatively small Machalilla National Park, where four

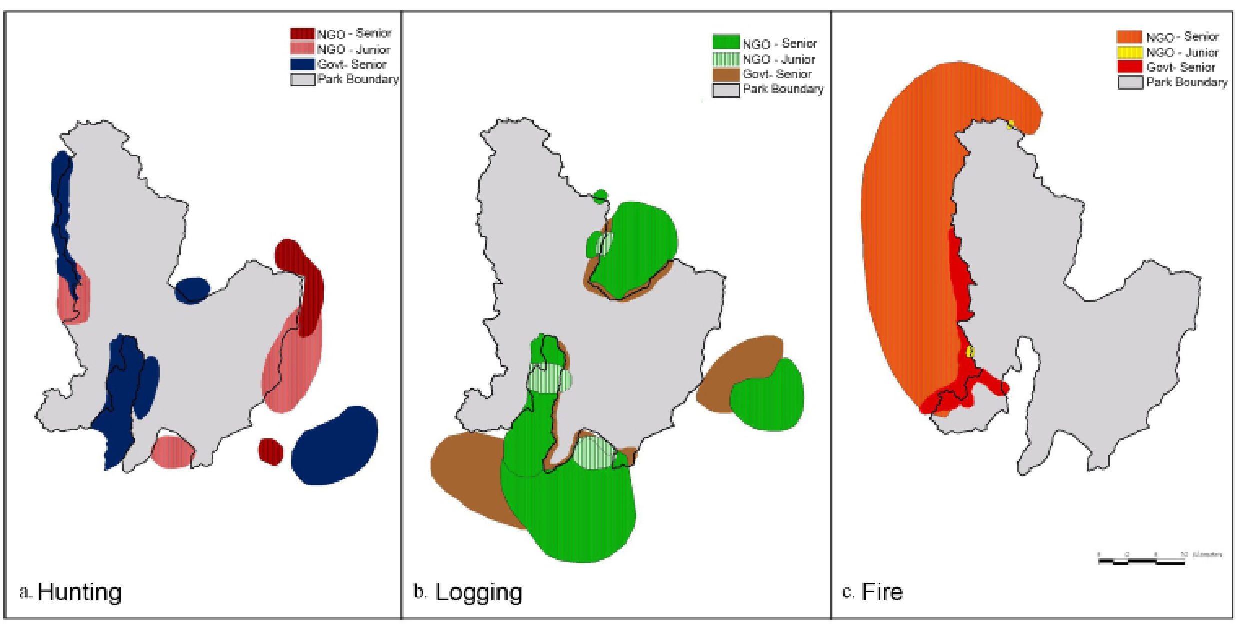

Figure 3 Sketch maps by three experts for hunting, logging, and fire in Podocarpus National Park, Ecuador.

Note: Experts often sketched resource use outside the PA boundaries, but we only recorded and analyzed estimates within the PA. Senior = >10 years experience on site, Junior = 5–10 years on site.

Table 4 Estimated area within park or reserve under extractive use according to expert interviews during 2000–2002.

Protected Area	Area under hunting, ha (% total area, ±SEM)	Area under logging, ha (% total area, ±SEM)	Area under grazing, ha (% total area)	Area under fires, ha (% total area)	Area under mining or oil extraction[1], ha (% total area)
IUCN I & II (strict protection)					
PN Bahuaja-Sonene	72,436 (5%, ±2%)	12,006 (1%, ±2%)	n/a[2]	n/a	14,882 (1%)
PN Machalilla[3]	11,908 (30%, ±1%)	19,218 (48%, ±13%)	6,047 (15%, ±4%)	n/a	107 (<1%)
RB Manu	104,636 (6%, ±4%)	98,415 (6%, ±5%)	51,325 (3%, nd)	51,325 (3%, nd)	14,155 (1%)
PN Podocarpus	14,122 (10%, ±3%)	9,702 (7%, ±11%)	2,542 (2%, nd)	3,476 (2%, ±3%)	133 (<1%)
PN Río Abiseo	15,624 (6%, ±2%)	n/a	21,542 (8%, nd)	31,450 (12%, nd)	85,074 (31%)
PN Sangay	151,672 (31%, ±8%)	47,469 (10%, nd[4])	195,375 (40%, ±10%)	n/a	28 (<1%)
PN Yanachaga-Chemillen	16,239 (15%, ±1%)	37,102 (34%, ±4%)	n/a	n/a	135 (<1%)
PN Yasuní	317,807 (31%, ±8%)	25,778 (3%, ±7%)	n/a	n/a	482,995 (48%)
Average %	**14%**	**5%**	**5%**	**2%**	**12%**
IUCN IV-VI (multiple use)					
BP Alto Mayo	48,557 (24%, ±6%)	37,032 (18%, ±6%)	n/a	n/a	n/a
RE Cayambe Coca	176,900 (43%, ±11%)	27,698 (7%, ±5%)	22,833 (6%, ±4%)	83,800 (21%, ±8%)	22,744 (6%)
RE Cotocachi Cayapas	23,678 (12% , ±3%)	23,134 (11%, ±7%)	25,150 (12%, ±2%)	n/a	328 (<1%)
RN Pacaya Samiria	499,921 (23%, ±3%)	741,845 (34%, ±5%)	n/a	27,793 (1%, nd)	n/a
BP Puipui	7,983 (15%, nd)	n/a	3,201 (6%, nd)	n/a	n/a
BP San Matias San Carlos	82,524 (55%, ±4%)	2,985 (2%, nd)	n/a	n/a	n/a
Average %	**26%**	**26%**	**2%**	**3%**	**1%**

[1] Area under mining or oil extraction was recorded from official maps, not expert interviews.
[2] For all n/a: experts did not report this type of use in area, or they judged it to be negligible.
[3] Terrestrial area only.
[4] For all nd: data are from one expert only or from consensus of experts interviewed simultaneously, thus SEM is not calculated.

respondents disagreed considerably about the percent of the park subject to logging (3–47%). There was greater agreement between experts in the estimates of resource-use intensity within each site. On a scale of one to five, experts' estimates differed by an average of 0.6 for logging, 1.0 for hunting, and 1.4 for livestock grazing.

To test for systematic bias in the resource uses drawn by different categories of experts, we compared the area and intensity of logging and hunting estimated by government employees versus those from representatives of nongovernmental organizations (NGOs) for the same PA. For this test, we calculated the mean difference in absolute area (not %) between pairs of observers from the same PA and pooled hunting and logging because these two uses did not diverge on this measure on average. Government vs. NGO representatives did not differ in absolute area on average ($n=45$ pairs, $t=-0.31$, $p=0.38$) or in the variance of this measure (F ratio=0.097, df=1, $p=0.76$). Similarly, government vs. NGO estimates of intensity of hunting and logging did not differ on this measure (F ratio=0.23, df=1, $p=0.63$). Across the PAs, we found no consistent differences between government and NGO respondents in grouped analyses (difference in area: mean $t=-0.06$, $p=0.94$, variances are equal, F ratio=0.01, $p=0.95$; difference in intensity: mean $t=1.68$, $p=0.10$, variances F ratio=2.94, $p=0.10$). Likewise, differences between experts in their years of local experience were not significantly correlated with differences in their estimates of area under extractive use or intensity of use (Spearman rho=-0.004, $p=0.98$; rho=-0.22, $p=0.17$).[4] Conclusive endorsement of this expert mapping method is hindered by a relatively small sample size, but our findings bolster other multistakeholder spatial threats assessments that present it as a valuable complement to other techniques (Bojorquez-Tapia et al. 2004; Treves et al. 2006).

Extractive resource use was widespread in the PAs according to the experts. Hunting was the most prevalent resource use, followed by logging and livestock grazing (Table 4). However, the experts reported that certain PAs were more imminently threatened by mining or petroleum extraction (e.g., Rio Abiseo National Park in Peru, Yasuni National Park in Ecuador). To evaluate the extent of extractive resource use within the PAs, we combined all the uses delineated by experts on the map for each PA. According to their combined estimates, the area of each

[4] It merits noting that we only interviewed experts with five years or more experience at the PA under assessment and the maximum experience was 40+ years.

PA under extractive resource use varied from 5 to 57% for the eight Peruvian PAs (average of 28%) and 15 to 70% for the seven Ecuadorian PAs (average of 43%) (Figure 4). Multivariate analysis revealed no significant linear relationship between the area under extractive use for each PA vs. the IUCN category, size or country, but again the relatively small sample limits the analysis.

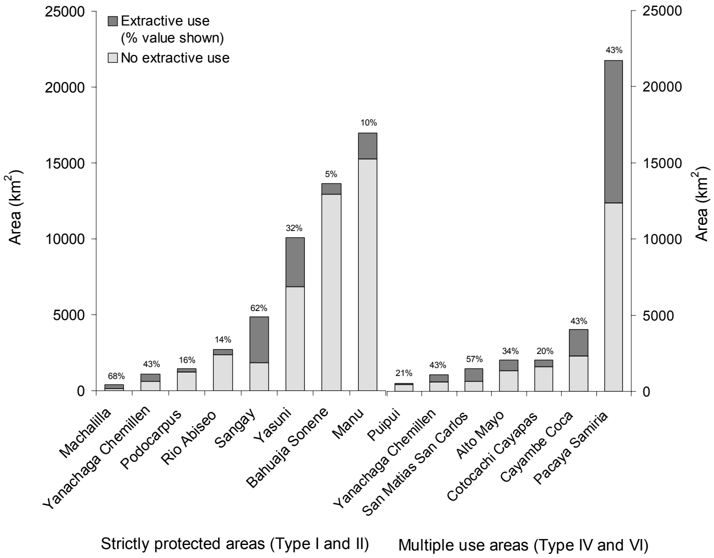

Figure 4 Area under extractive use within 14 parks and reserves in Ecuador and Peru

Discussion

Expansion and Reclassification of PAs

The 15 PAs in this study have in aggregate nearly doubled in size since their creation. This growth mirrors national and regional trends. According to the World Database on Protected Areas (WDPA), the system of IUCN Category I–VI protected areas for Ecuador grew by 26% between 1990–2005 and the Peruvian system grew by 20% during those same years (WDPA Consortium, 2005). More broadly, IUCN data indicate that, relative to other regions, South American PA systems experienced an extraordinary expansion during 1986–1997 (Zimmerer et al. 2005). Although these databases are subject to error (West & Brockington, 2006), the regional growth of PAs during the past 30 years is significant and reflects both the expansion of existing PAs (as in the case of the 15 PAs studied here) and the creation of new parks and reserves. We also discovered that more area was added for multiple use within the seven Ecuadorian parks versus more for strict protection in the eight Peruvian PAs (Table 2). This mixed result does not resolve debate regarding the relative dominance of strictly protected versus multiple-use land in newly expanded conservation territories in developing countries (Naughton-Treves et al. 2005; Zimmerer et al. 2005). Moreover, our results require careful interpretation for two reasons: 1) our Peruvian sample was swamped by events in the Department of Madre de Dios where large sections of a vast transitory multiple-use reserve (Tambopata-Candamo) was upgraded to a national park (Bahuaja-Sonene) (Alvarez & Naughton-Treves, 2003), and 2) our original selection criteria favored large PAs older than 10 years. Therefore, our data do not reflect the recent proliferation in both countries of many smaller, multiple-use PAs (i.e., at a national level, the Peruvian protected area system now designates more land for multiple use than for strict protection) (Instituto Nacionalde Recursos Naturales, 2006).

The Current Extent of Human Resource Use within PAs

Expert mapping suggests that extractive resource use is common within the 15 Andean PAs. Hunting, in particular, was widespread and covered an average of 14% of strictly protected and 26% of multiple-use areas (n=8 strictly protected areas, range: 5–33%; n=6 multiple use, range: 12–55%) (Table 4). This accords with Fa, Peres, & Meeuwig's (2002) observation that hunting is the most geographically widespread resource use in tropical forests and permeates even remote reserves (Peres & Terborgh, 1995; Rubio del Valle, 2002). In fact, in most of the PAs, experts reported that hunting was more prevalent *within* park boundaries than in outside areas where valuable game species had been reduced or extirpated (Naughton-Treves et al. 2003). Paradoxically, the presence of hunting in a PA can be interpreted as a sign of park effectiveness (game are still plentiful enough within the PA to attract hunters) and as a threat (given that this wildlife may soon be depleted). Similarly, hunting-free regions within PAs may signal well-protected wildlife, or conversely, wildlife that has been so depleted that hunters have moved on. Programs to monitor hunting and to improve its sustainability are urgent for this region, given the activity's ecological significance and its importance in providing protein for the rural poor (Bodmer & Lozano, 2001).

Respondents identified logging as a threat to all but two of the PAs (Table 4). The location and extent of logging was subject to the greatest interobserver variation of any activity, but on average logging affects approximately 5% of strictly PAs and approximately 26% of multiple-use areas. Fewer PAs were affected by mining and petroleum extraction, though these activities seriously endangered only two parks (Rio Abiseo in Peru and Yasuni in Ecuador). Other parks (Podocarpus in Ecuador and Bahuaja-Sonene in Peru) were threatened by "artesanal" mining, an activity seldom registered on official concession maps (Tello et al. 1998).

Despite widespread human activities within their boundaries, these 15 protected areas (PAs) are not simply "paper parks." Remote sensing data were available for nine of the PAs, all of which experienced average deforestation rates of < 0.11% per year during 1991–2001 (Steininger, 2006), a rate lower than regional averages (Alvarez & Naughton-Treves, 2003). Avoiding deforestation is not the ultimate litmus test for parks, but intact forest is an important signal that PAs are having substantive impacts on land-use changes (Bruner et al. 2001). Among the activities invisible to remote sensing, hunting in tropical forests is seldom sustainable (Robinson & Redford, 1994) and may represent a threat to basic ecosystem function due to the importance of wildlife as seed dispersers and predators (Redford, 1992; Peres & Lake, 2003). Others counter that hard evidence is too sparse to conclude that hunting is compromising forest integrity (Schwartzman et al. 2000); or they acknowledge possible overhunting but point to the success of local communities in defending forests from other threats, including fire and conversion to agriculture (Nepstad et al. 2006). Assessing the sustainability of hunting and other extractive activities is beyond this scope of this study, but our findings suggest that remotely sensed deforestation offers a highly conservative estimate of the actual area under human use. This underscores the value of using multiple methods for assessing the extent of human resource use in forested areas.

Disparities between the Legal Status of Protected Areas and Actual Management

According to our interviews with local experts, the expansion of PAs in Peru and Ecuador was motivated by a desire to protect critical habitats and watersheds left out of original delimitations (Peres, 2005). But PA managers also noted that such enlargements were often conducted in the context of scarce or highly uneven data regarding local land use and human settlements (Peres, 2002). This uncertainty partly explains the disparity between the legal status of some PAs and their actual management. Some managers also explained that there was no choice but to incorporate areas under human use or settlement given that "empty" wilderness areas simply did not exist. As a result, large portions of PAs legally designated for strict protection (IUCN category I or II) are subject to extractive resource use. For example, according to local experts, approximately 30% of Machalilla National Park in Ecuador and approximately 50% of Yanachaga National Park in Peru (both Type II PAs) are free from hunting, logging, and livestock grazing (see Fiallo & Naughton-Treves, 1998; Yallico & Rose, 1998 for a history of these two areas). Forty-eight percent of Yasuni National Park in Ecuador is threatened by petroleum extraction or exploration (Table 4). By IUCN convention, Type I and II areas should protect at least 75% of their total area from extractive use (Phillips, 2003).

Widespread extractive resource use within national parks not only contradicts international conventions, but is legally prohibited in both Ecuador and Peru, as is human settlement in national parks (Government of Ecuador, 1981; Consejo Nacional del Medioambiente, 2000). Ecuador's 1981 Forestry Law goes on to bar extraction in ecological reserves, but obliges the government to purchase any titled land within parks or ecological reserves; a stipulation that has rarely been met (Government of Ecuador, 1981).

In recent years, Ecuadorian conservationists have discussed revising national law to acknowledge individually and collectively owned land inside PAs, hoping that legalizing human presence would improve the likelihood of sustainable and regulated use. However, this proposal has raised such heated debate over indigenous and ancestral land rights, the legitimacy of informal versus formal property claims, and other controversial issues that after a preliminary discussion the Ecuadorian Congress abandoned it.

As another means to resolve contradictions between legal status and actual practice, some international conservationists contend that parks with incongruent classifications, such as Machalilla and Yanachaga, should be reclassified as multiple-use reserves (Terborgh & Davenport, 2004). But local conservation NGOs are concerned that "downgrading" an area may result in lower levels of international funding or tourism and create a bad precedent for other PAs (Fiallo & Naughton-Treves, 1998).

We also discovered another, less controversial discrepancy in legal status versus actual PA management. Some Type VI areas in this study had large areas free from extractive use. Experts estimated nearly 80% of Ecuador's Cotocahi Cayapas Ecological Reserve and 67% of Peru's Alto Mayo Reserve (both Type VI PAs) were free from extractive use. However, both reserves face increasing resource pressure, particularly for logging (Rudel, 2000).

The discrepancy between legal status and actual management is common to many Latin American PAs and can lead to significant conflict, particularly if PA boundaries are ambiguous or disputed (Brandon & Wells, 1992; Bojorquez-Tapia et al.

2004). For example, some PA field staff complained that the disparity between PA legal code and accepted practice undermined their authority and hindered enforcement. Other local experts revealed that although some managers attempted to "correct" such discrepancies by evicting people from PAs and/or excising occupied land from parks during the 1970s and 1980s, these strategies have been replaced by a more integrated approach with respect to local populations. In fact, several PA managers indicated they were not particularly concerned with official IUCN categories and that some "pragmatic ambiguity" about resource use was necessary to avoid conflict and to build local alliances.

The Importance of Indigenous Reserves

A particularly important and controversial aspect of resource use within PAs concerns the territorial claims and rights of indigenous people. Both Ecuador and Peru legally allow subsistence use by indigenous or "ancestral" people within some PAs. A thorough treatment of indigenous territories is beyond the scope of this paper, but it is essential to stress the contributions of indigenous areas to biodiversity conservation (Peres & Zimmerman, 2001; Holt, 2005; Nepstad et al. 2006). The growth of indigenous territories and reserves in Ecuador and Peru during the past two decades has outpaced the growth documented for the 15 PAs in this study. For example, the area of land titled to indigenous groups in the Peruvian Amazon increased from nearly 74,000 km² in 1977 to 105,000 km² in 1999 (for lands titled as "comunidades nativas" under Peruvian law). An additional 28,120 km² have been declared as indigenous territorial reserves for those communities living in isolation (GEF/PNUD/UNOPS, 1997; PETT, 1999). Across Ecuador, the land designated as "ethnic reserves" and "ethnic areas" surpasses 10 million ha (Fundacion Natura, 2005). An accurate comparison of the area dedicated to indigenous territories versus state-managed national parks and reserves is not possible due to overlapping claims and legal ambiguities in land classification. In some cases, indigenous groups have exclusive legal rights to areas within national parks (e.g., the Machiguenga in Manu National Park) (Terborgh & Davenport, 2004; Terborgh & Peres, 2004). In other instances, the presence of indigenous people has been formally accepted within PAs (in practice and in official management plans), but their territories are not legally delineated (e.g., the Agua Blanca people in Machalilla National Park) (Fiallo & Naughton-Treves, 1998; INEFAN, 1998). In both Ecuador and Peru, indigenous territories are too often undermined by illicit resource use by outsiders or by mining or petroleum concessions issued by the government (IBC, 2005). While the explicit interest of indigenous communities may not be biodiversity conservation per se (Fiallo & Naughton-Treves, 1998; INEFAN, 1998; Holt, 2005), the coincidence of interests between indigenous peoples and conservationists, especially given large-scale external threats, is frequently high. The fact that indigenous groups usually manage land and resources collectively (as opposed to private parcels) improves chances for sustainable use, particularly for fugitive resources like wildlife (Naughton-Treves et al. 2003; Schwartzman & Zimmerman, 2005). Although alliances between indigenous peoples and conservationists are not always straightforward, these collaborations can have tremendous importance for both biodiversity and human welfare (Schwartzman & Zimmerman, 2005).

Current Trends in Protected Area Management: Zoning and Collaboration

In the majority of our study sites, management agencies have initiated zoning projects of varying scope to regulate resource use within PAs, in some cases (e.g., Machalilla National Park) allocating land for resource use within Type II areas. Ideally, these zoning projects provide a way to balance conservation aims with economic development goals across large areas and among diverse stakeholders. Zoning potentially allows the needed flexibility to draw boundaries that acknowledge preexisting claims and/or highlight areas of special ecological importance. However, zoning can also be a purely political maneuver to postpone or prevent enforcing unpopular rules or confronting powerful commercial interests. In such cases, zoning may reduce the size of PAs and set a precedent for carving them up (Terborgh & Peres, 2004). To date, zoning exercises in most of the 15 case study PAs have suffered from serious implementation problems. Some of the community representatives that we interviewed complained that the zoning process was not truly "participatory." Park staff meanwhile admitted that actual enforcement activities seldom matched the complexity of the elaborate zoning plans resting on office shelves. Managers and community representatives agreed that the rules of resource use and location of zones within PAs were often unclear. In the worst cases, "paper zones" have been drawn in "paper parks," leaving forest ecosystems and legitimate forest residents both at risk. Future zoning efforts are more likely to be implemented effectively if they are scaled to managerial capacity and are viewed as legitimate by local citizens and key stakeholder groups.

The rezoning of areas to assign locations where various uses are permissible is equivalent to the biosphere-reserve concept that includes one or several protected areas (core areas), but also allows for the presence of people and internal zoning to regulate a variety of uses. Although the biosphere model is often viewed as more accommodating to local people, evidence suggests that some of these areas may impose significant social costs that over time can burden local populations (Brandon, 1997; Holt, 2005). These communities will likely remain poor if they rely entirely on non-timber forest resources (Byron & Arnold, 1999; Vedeld et al. 2004). The experiences to date with biosphere reserves suggest the necessity of formalized agreements with local residents that are periodically revisited. Residents themselves may often be the first to see that existing patterns are, in fact, not sustainable (Holt, 2005). Issues of transparency, social justice, and poverty reduction are therefore paramount within these greatly expanded biosphere reserve-type managed areas.

Agrawal's (2001) synthesis of 20 years of research on common pool resource management offers important lessons for managing land for human welfare concerns and biodiversity. From his review, Agrawal concludes that sustainable and successful resource management is shaped by many factors, but is most likely when: 1) boundaries are clearly defined, 2) rules are easily understood and enforced, 3) user groups live near the resource, 4) there is external support for sanctions, and 5) monitoring and enforcement systems are in place. Achieving these "conditions" for sustainability in inhabited areas of Ecuadorian and Peruvian PAs is a tremendous challenge. For example, with regard to enforcement, Stern (2007) documents that in the over 20 years since Podocarpus National Park was created in Ecuador, park offenders have been punished only in a few instances, with equipment and harvested timber seizures. No arrests have ever been made and no fines have been levied. Government agencies themselves too often undermine PAs, such as when they issue mining or petroleum concessions within parks (Chicchón, 2000). Successful PA management will require substantial increases in financial and legal support. Both Ecuador and Peru are attempting to reform their PA management by promoting co-management and/or decentralized administration for some areas. The outcome of these reforms is uncertain (Rubio del Valle, 2002). The more promising examples of PA co-management include an initiative led by the Cofan, an indigenous group of Ecuador (Lundmark, 2002), and one by a municipal water company, Empresa Municipal de Telecomunicaciones, Agua Potable, Alcantarillado y Saneamiento Ambiental (Echavarria et al. 2004; Nyce, 2004).

Conclusion

If our findings of disparities between legal status and actual management prove common beyond Ecuador and Peru, conservationists may be further from the Rio Convention's 10% set-aside target than international datasets currently suggest. IUCN categories constitute an important "common language" and ideally enable comparisons of PA coverage and management status at regional and global scale (Chape et al. 2005). However, our study reveals that PA categorization is a dynamic and sometimes ambiguous process, with incongruities as common as accurate classifications. Although international accords and policies suggest that conservation strategies and rules are being globalized and homogenized (West & Brockington, 2006), our results show that, for better or worse, PA management in practice remains variable and idiosyncratic, if only because political realities and budgetary constraints hinder conforming to international guidelines.

Our study documents the substantial expansion of 15 PAs in Ecuador and Peru despite widespread human presence and resource use within these areas. According to Terborgh & Peres (2004), the majority of parks in developing countries are similarly affected by human activity and this human presence is a "time bomb." Other experts are more optimistic and see resident peoples as real or potential forest defenders (Schwartzman et al. 2000). Ultimately, the long-term conservation impact of the 15 PAs in this study will turn on clarifying rules of resource access and distribution and building alliances among diverse stakeholders. None of the 63 experts that we interviewed proposed large-scale evictions or land-purchase programs to remove people from PAs. Nor did they propose the degazettement of a PA or excisement of occupied areas. Thus, the challenge ahead for Ecuadorian and Peruvian conservationists is to resolve thorny political issues regarding who has legitimate claims to resources within PAs and where, and to seek solutions that make conservation possible in complex contexts. One key need is to act quickly to protect the existing intact forest areas from commercial activities. Resolving these issues is urgent given the increased intensity of resource use and forest clearing in the region. As lands outside of PAs are increasingly developed, conserving biodiversity requires protecting core areas and negotiating equitable and ecologically sustainable management rules for areas designated for extractive use.

References

Agrawal, A. 2001. Common property institutions and sustainable governance of resources. *World Development* 29(10):1649–1672.

Alvarez, N. & Naughton-Treves, L. 2003. Linking national agrarian policy to deforestation in the Peruvian Amazon: a case study of Tambopata, 1986–1997. *Ambio* 32(4):269–274.

Bodmer, R. & Lozano, E. 2001. Rural development and sustainable wildlife use in Peru. *Conservation Biology* 15(4):1163–1170.

Bojorquez-Tapia, L., de la Cueva, H., Diaz, S., Melgarejo, D., Alcantar, G., Jose Solares, M., Grobet, G., & Cruz-Bello, G. 2004. Environmental conflicts and nature reserves: redesigning Sierra San Pedro Martir National Park, Mexico. *Biological Conservation* 117(2):111–126.

Brandon, K. & Wells, M. 1992. Planning for people and parks: design dilemmas. *World Development* 20(4):557–570.

Brandon, K. 1997. Policy and practical considerations in land-use strategies for biodiversity conservation. In R. Kramer, C. van Schaik, & J. Johnson (Eds.), *Last Stand. Protected Areas and the Defense of Tropical Biodiversit.* pp. 90–111. New York: Oxford University Press.

Bruner, A., Gullison, R., Rice, R., & Fonseca, G. 2001. Effectiveness of parks in protecting tropical biodiversity. *Science* 291(5501):125–128.

Byron, N. & Arnold, M. 1999. What future for rainforest peoples? *World Development* 27(5):789–805.

Chape, S., Harrison, J., Spalding, M., & Lysenko, I. 2005. Measuring the extent and effectiveness of protected areas as an indicator of meeting global biodiversity targets. *Philosophical Transactions of the Royal Society B* 360(1454):443–455.

Chicchón, A. 2000. Conservation theory meets practice. *Conservation Biology* 14(5):1368–1369.

Consejo Nacional del Medioambiente. 2000. Expansión de las Áreas Naturales Protegidas. http://www.conam.gob.pe/geo/ii24.htm. August 24, 2006.

DeFries, R., Hansen, A., Newton, A., & Hansen, M. 2005. Increasing isolation of protected areas in tropical forests over the past twenty years. *Ecological Applications* 15(1):19–26.

Doolittle, A. 2003. Finding a new direction during a participatory community mapping project. *Tropical Resources Bulletin* 22:74–78.

Echavarria, M., Vogel, J., Alban, M., & Meneses, F. 2004. *The Impacts of Payments for Watershed Service in Ecuador*. London: International Institute for Environment and Development.

Fa, J., Peres, C., & Meeuwig, J. 2002. Bushmeat exploitation in tropical forests: an intercontinental comparison. *Conservation Biology* 16(1):232–237.

Fiallo, E. & Naughton-Treves, L. 1998. Ecuador: Machalilla National Park. In K. Brandon, K. Redford, & S. Sanderson (Eds.), *Parks in Peril. People, Politics, and Protected Areas.* pp. 249–287. Covelo, CA: Island Press.

Fundacion Natura. 2005. Boletin Informativo. http://www.fnatura.org/paginas/textos.php?id=14&val=0. August 18, 2006.

GEF/PNUD/UNOPS. 1997. *Amazonía Peruana, Comunidades Indígenas, Conocimientos y Tierras Tituladas: Atlas y Base de Datos.* Lima: PNUD.

Geisler, C. & De Sousa, R. 2000. From refuge to refugee: the African case. *Public Administration and Development* 21(2):159–170.

Ghimire, K. 1994. Parks and people: livelihood issues in national parks management in Thailand and Madagascar. *Development and Change* 25(1):195–229.

Ghimire, K. & Pimbert, M. 1997. Social change and conservation. In K. Ghimire & M. Pimbert (Eds.), *Social Change and Conservation*. pp. 1–45. London: Earthscan.

Government of Ecuador. 1981. *Ley Forestal y de Conservación de Áreas Naturales y Vida Silvestre es de 1981.* Ley No. 74. Registro Oficial 64 del 24 de agosto de 1981.

Holt, F. 2005. The Catch-22 of conservation: indigenous peoples, biologists, and cultural change. *Human Ecology* 33(2):199–215.

Instituto del Bien Común (IBC). 2005. Information System on Native Communities of the Peruvian Amazon (SICNA). http://www.ibcperu.org/index.php?lg=EN&slt_rb=1033. August 20, 2006.

Instituto Ecuatoriano Forestal y de Areas Naturales (INEFAN). 1998. *Plan de Manejo de la Reserva. Ecológoca Cayambe Coca.* Annexo número 1. Quito: Compilación técnica-científica de los recursos naturales y aspectos socioeconómicos de la RECAY.

Instituto Nacionalde Recursos Naturales. 2006. Sistema Nacional de Áreas Naturales Protegidas por el Estado. http://www.inrena.gob.pe/ianp/ianp_sistema_sinanpe.htm. October 18, 2006.

International Union for the Conservation of Nature (IUCN). 2004. The Durban Action Plan, revised version. IUCN Fifth World Parks Congress. Durban, South Africa. http://www.iucn.org/themes/wcpa/wpc2003/pdfs/outputs/wpc/durbanactionplan.pdf.

Landeo, C. 2006. Personal Communication. Director, Tambopata National Reserve, Institute for Natural Resources, Peru. July 19.

Locke, H. & Dearden, P. 2005. Rethinking protected area categories and the new paradigm. *Environmental Conservation* 32(1):1–10.

Lundmark, K. 2002. Protecting biodiversity. *Bioscience* 52(5):456.

Myers, N., Mittermeier, R., Mittermeier, C., da Fonseca, G., & Kent, J. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403(6772):853–858.

Naughton-Treves, L., Mena, J., Treves, A., Alvarez, N., & Radeloff, V. 2003. Wildlife beyond national park boundaries: the impact of slash and burn farming and hunting on wildlife in Tambopata, Peru. *Conservation Biology* 17(4):1106–1117.

Naughton-Treves, L., Holland, M., & Brandon, K. 2005. The role of protected areas in conserving biodiversity and sustaining local livelihoods. *Annual Review of Environment and Resources* 30:219–252.

Nepstad, D., Schwartzman, S., Bamberger, B., Santilli, M., Ray, D., Schlesinger, P., Lefebvre, P., Alencar, A., Prinz, E., Fiske, G., & Rolla, A. 2006. Inhibition of Amazon deforestation and fire by parks and indigenous lands. *Conservation Biology* 20(1):65–73.

Nyce, C. 2004. The decentralization of protected area management in Ecuador: the Condor Bioreserve and Cajas National Park initiatives. *Journal of Sustainable Forestry* 18(2-3):65–90.

Pearce, J., Cherry, K., Drielsma, M., Ferrier, S., & Whish, G. 2001. Incorporating expert opinion and fine-scale vegetation mapping into statistical models of faunal distribution. *Journal of Applied Ecology* 38(2):412–424.

Peres, C. 2002. Expanding conservation area networks in the last wilderness frontiers: the case of Brazilian Amazonia. In J. Terborgh, C. Van Schaik, L. Davenport, & M. Rao (Eds.), *Making Parks Work: Strategies for Preserving Tropical Nature.* pp.137–148. Washington, DC: Island Press.

Peres, C. 2005. Why we need megareserves in Amazonia. *Conservation Biology* 19(3):728–733.

Peres, C. & Terborgh, J. 1995. Amazonian nature reserves: an analysis of the defensibility status of existing conservation units and design criteria for the future. *Conservation Biology* 9(1):34–46.

Peres, C. & Zimmerman, B. 2001. Perils in parks or parks in peril? Reconciling conservation in Amazonian Reserves with and without use. *Conservation Biology* 15(3):793–797.

Peres, C. & Lake, I. 2003. Extent of nontimber resource extraction in tropical forests: accessibility to game vertebrates by hunt-

ers in the Amazon Basin. *Conservation Biology* 17(2):521–535.
Phillips, A. 2003. Turning ideas on their head: the new paradigm for protected areas. *The George Wright Forum* 20(2):1–25.
Proyecto Especial de Titulación de Tierras (PETT). 1999. *Directorio de Comunidades Nativas del Perú*. Lima: Ministerio de Agricultura.
Redford, K. 1992. The empty forest. *Bioscience* 42(6):412–422.
Robinson, J. & Redford, K. 1994. Measuring the sustainability of hunting in tropical forests. *Oryx* 28(4):249–256.
Rubio del Valle, F. 2002. The national sanctuary Pampas del Heath: case study of a typical "paper park" under management of an NGO. In J. Terborgh, C. Van Schaik, L. Davenport, & M. Rao (Eds.), *Making Parks Work: Strategies for Preserving Tropical Nature.* pp.149–155. Washington, DC: Island Press.
Rudel, T. 2000. Organizing for sustainable development: conservation organizations and the struggle to protect tropical rain forests in Esmeraldas, Ecuador. *Ambio* 29(2):78–82.
Schwartzman, S., Moreira, A., & Nepstad, D. 2000. Rethinking tropical forest conservation: perils in parks. *Conservation Biology* 14(5):1351–1357.
Schwartzman, S. & Zimmerman, B. 2005. Conservation alliances with indigenous peoples of the Amazon. *Conservation Biology* 19(3):721–728.
Steininger, M. 2006. *Landsat Image Analysis of Deforestation in Ecuadorian and Peruvian Protected Areas, ~1990–2000.* Unpublished work. Director of Remote Sensing and GIS Laboratory. Washington, DC: Conservation International.
Stern, M. 2007. Payoffs vs. process: expanding the paradigm for park/people studies beyond economic rationality. *Journal of Sustainable Forestry,* in press.
Suárez de Freitas, G. 2002. Personal Communication. Director of Protected Areas, Institute for Natural Resources, Peru. August 11.
Tello, B., Fiallo, E., & Naughton-Treves, L. 1998. Podocarpus National Park. In K. Brandon, K. Redford, & S. Sanderson (Eds.), *Parks in Peril: People, Politics, and Protected Areas.* pp. 287–322. Covelo, CA: Island Press.
Terborgh, J. & Davenport, L. 2004. Monitoring protected areas. In J. Terborgh, C. Van Schaik, L. Davenport, & M. Rao (Eds.), *Making Parks Work: Strategies for Preserving Tropical Nature.* pp. 395–408. Washington, DC: Island Press.
Terborgh, J. & Peres, C. 2004. The problem of people in parks. In J. Terborgh, C. Van Schaik, L. Davenport, & M. Rao (Eds.), *Making Parks Work: Strategies for Protecting Tropical Nature.* pp. 307–319. Washington, DC: Island Press.
Treves, A., Andiamampianina, L., Didier, K., Gibson, J., Plumptre, A., Wilkie, D., & Zahler, P. 2006. A simple, cost-effective method for involving stakeholders in spatial assessments of threats to biodiversity. *Human Dimensions of Wildlife* 11(1):43–54.
Vedeld, P., Angelsen, A., Sjaastad, E., & Berg, G. 2004. *Counting on the Environment Forest Incomes and the Rural Poor*. Environment Department Paper No. 98. Washington, DC: The World BanK.
WDPA Consortium. 2005. World Database on Protected Areas. http://www.unep-wcmc.org/wdpa/. February 1, 2005.
West, P. & Brockington, D. 2006. An anthropological perspective on some unexpected consequences of protected areas. *Conservation Biology* 20(3):609–616.
Yallico, L. & Rose, D. 1998. Yanachaga-Chemillen National Park. In K. Brandon, S. Sanderson, & K. Redford (Eds.), *Parks in Peril.* pp. 353–374. Washington, DC: Island Press.
Yamada, K., Elith, J., McCarthy, M., & Zerger, A. 2003. Eliciting and integrating expert knowledge for wildlife habitat modelling. *Ecological Modelling* 165(2-3):251–264.
Zimmerer, K., Galt, R., & Buck, M. 2005. Globalization and multi-spatial trends in the coverage of protected-area conservation (1980–2000). *Ambio* 33(8):520–529.

ARTICLE

Deforestation, malaria, and poverty: a call for transdisciplinary research to support the design of cross-sectoral policies

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Many of the world's poorest people live in areas with high malaria rates and suffer the associated physical, economic, and social hardships. These same areas are often undergoing extensive forest conversion and degradation. While causality has generally not been established, the scientific literature makes it abundantly clear that the juxtaposition of deprivation, deforestation, and disease is not pure coincidence. We chart a course for using transdisciplinary research to develop more effective policies to control malaria, protect forests, and alleviate poverty. First describing the malaria problem, including its etiologic roots and its social toll, the paper then examines some shortcomings of contemporary societal responses. We discuss why understanding the role of deforestation in linking malaria to poverty is important and present the mixed empirical evidence on the malaria-deforestation-poverty link from macro- and microeconomic studies. The paper concludes with a proposal for strategically linking research and policy at the malaria-deforestation-poverty nexus in a comprehensive decision-analysis framework that channels research to the most pressing policy needs, informs policy with the most conclusive research, and ensures stakeholders are effectively informed about their options.

KEYWORDS: deforestation, malaria, antipoverty programs, economic conditions, health policy, environmental policy, developing countries

Introduction

Many of the world's poorest people live in areas with high malaria rates and suffer the resulting physical, economic, and social hardships (see Figure 1). Many of these same locales are also undergoing rapid and extensive forest conversion and degradation (see Figure 2). Despite the investment of billions of dollars in policies to slow deforestation, eradicate malaria, and foster economic development, about a third of the world's population (2 billion people) live in malaria-infected areas, deforestation continued at the rate of 16 million hectares annually throughout the last decade, and about half the world's population lives on less than US$2 per day. More people currently die from malaria than was the case forty years ago. The illness is a "reemerging" threat due to its expanded distribution, heightened local incidence, and increased severity, duration, and resistance to treatment (Wilcox & Colwell, 2005; Greenwood et al. 2005). Recognizing that we live in a global society in which ecological, epidemiological, and economic phenomena truly connect us all, we take seriously the challenge put forward by Guerin et al. (2002) that we "cannot ignore the strategic and moral imperative of alleviating the suffering of a significant number of the world's people."

The design and implementation of policies to combat malaria and to mitigate its consequences require clear understanding of the interrelations between deforestation, poverty, and malaria and the cross-effects (or unintended side effects) of policies targeting each of these three problems. For example, how do deforestation policies affect malaria and poverty? While causality still remains elusive, the scientific literature makes it abundantly clear that the juxtaposition of deprivation, deforestation, and disease cannot be dismissed as pure coincidence. Therefore, more rigorous research and evaluation methods are necessary to better comprehend the complex relationships among these factors and to identify causes and effects that public policy and private action can mitigate. Toward that end, we argue that policy options for malaria control would be enhanced by the appli-

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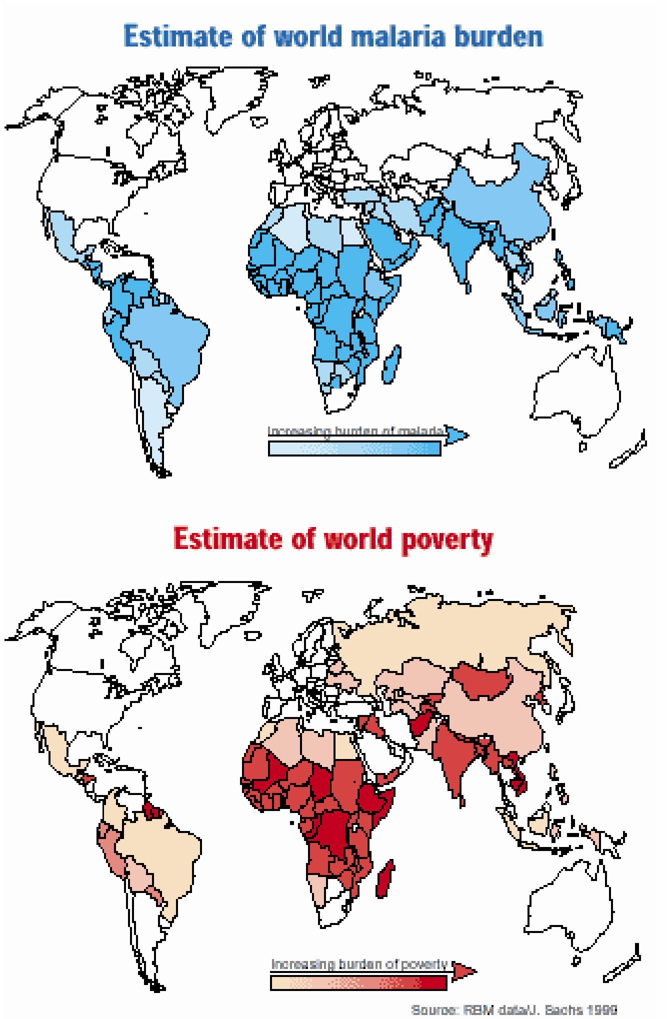

Figure 1 Malaria and poverty in 1995 (WHO, 2001)

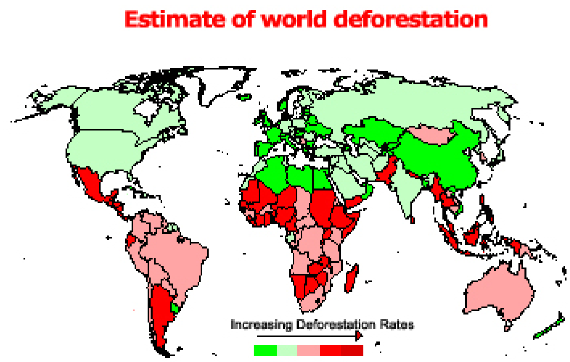

Figure 2 Forest cover change from 1990–2000 (FAO, 2001)

cation and dissemination of transdisciplinary research that integrates economics, ecology, and epidemiology to examine the critical nexus of malaria, deforestation, and economic development.

This paper charts a course for using transdisciplinary research to develop more effective policies to control malaria, protect forests, and alleviate poverty. We are not alone in advocating an approach that recognizes the interrelationships among ecology, human behavior, economics, epidemiology, physical processes, and other factors (e.g., Parkes et al. 2003). Kates et al. (2001) call for "sustainability science," which the authors describe as a new field that "seeks to understand the fundamental character of interactions between nature and society" and involves "problem-driven, interdisciplinary research." Focusing specifically on emerging and reemerging infectious diseases, Wilcox & Colwell (2005) argue that "a more realistic view [of these] diseases requires a holistic perspective that incorporates social as well as physical, chemical, and biological dimensions of our planet's systems." These authors use the term "biocomplexity" to describe this approach, noting that others have used similar arguments to advocate approaches premised on "socioecological systems" (Berkes & Folke, 1998), "human-natural systems" (Gunderson & Holling, 2002), or "eco-epidemiology" (Kaufman & Poole, 2000). We add our voices to this chorus calling for comprehensive frameworks to facilitate better understanding and more effective solutions to complex environmental and social problems such as malaria.

This paper first describes the malaria problem, including its etiologic roots, its health effects, and its economic and social toll on affected populations. We then examine how individuals, households, governments, and the public-health profession have traditionally responded to malaria threats through prevention, control, and treatment measures, and identify some shortcomings of these approaches. This leads us into a discussion of one arguably under-researched area—the ecological link between deforestation, malaria vectors, and disease incidence. Because of the well-documented link between poverty and deforestation, especially in the tropics, we propose and discuss five specific reasons for assessing the role of deforestation in linking malaria to economic development. We present the mixed empirical evidence on the malaria-deforestation-poverty link from macro- and micro-economic studies and conclude that more refined research methods at both scales can help identify these causal connections. Building on knowledge gaps identified in the paper, we conclude with a proposal to strategically link research and policy at the malaria-deforestation-poverty nexus in a comprehensive decision-analysis framework that channels research to the most pressing policy needs, informs policy with the most conclusive findings, and ensures that stakeholders are effectively informed about their options.

The Malaria Burden

Malaria is a vector-borne disease caused by protozoan parasites (e.g., *Plasmodium falciparum*) that complete their complex cycle of development alternating between human hosts and mosquitoes of the genus *Anopheles*. The burden of this disease on human populations in malarial regions is devastating. As Sachs & Malaney (2002) describe:

> The numbers are staggering: there are 300 to 500 million cases every year; and between one to three million deaths, mostly of children, attributed to this disease. Every 40 seconds a child dies of malaria, resulting in a daily loss of more than 2,000 young lives worldwide. These estimates render malaria the pre-eminent tropical parasitic disease and one of the top three killers among communicable diseases.

Beyond mortality, malaria causes morbidity through fever, weakness, malnutrition, anemia, spleen disorders, and vulnerability to other diseases. Malarious patients also experience asymptomatic parasitemia, acute febrile, chronic debilitation, and pregnancy complications (Bremen, 2001). Malaria's global impact on human health, productivity, and general well being is profound, with joint mortality and morbidity impacts estimated to be 45 million disability adjusted life years (DALYs) in 2000, an amount equal to nearly 11% of all infectious diseases (Guerin et al. 2002). Moreover, as with other diseases, the malaria burden is experienced disproportionately by some of the most vulnerable populations, in particular children and pregnant women.

Social scientists, especially economists, have studied malaria's social and economic impacts at several scales, peering inside families, looking across households and communities, and comparing entire nations and continents. What these researchers have found is remarkably consistent—malaria imposes substantial social and economic costs and impedes economic development through several channels, including quality of life, fertility, population growth, savings and investment, labor productivity, premature mortality, and medical costs (Sachs & Malaney, 2002).

Economists have sought to put a monetary value on this burden by measuring the impacts on households, health systems, and national economies. At the household level, malaria imposes both direct and indirect costs. Direct costs include time lost from work as well as the cost of medical treatment (including transportation and medical care). Indirect costs, which are typically harder to measure, include loss of work efficiency and time and work reallocation within the household. For children in particular, indirect costs also include nutritional deficiencies, cognitive and educational disabilities, and physical retardation. Pain and suffering are clearly substantial costs of malaria, but are perhaps most difficult to quantify and monetize. In general, long-term effects, such as child development and compromised immunity, are unknown (Hutubessy et al. 2001).

At the level of health-care systems, economists typically focus on treatment and medication costs. In most economies, households are subsidized for treatment and medication and other expenses are borne by the health system. There are also opportunity costs for displaced or delayed treatment and medications for other family members, while caregivers lose workdays.

These direct and indirect impacts can collectively impede economic development and growth. Malaria is estimated to decrease annual per capita GNP growth by 0.25-1.30% in tropical countries, after accounting for initial endowments, overall life expectancy, and geographic location (Guerin et al. 2002; Sachs & Malaney, 2002). To the extent that slow economic growth limits malaria-control funds, there is a vicious cycle of poverty and malaria that diminishes economic opportunities for huge numbers of people.

Societal and Individual Responses

Societies respond to the malaria burden in several ways, broadly grouped into preventive (control) and curative (treatment) approaches. The efficacy of both approaches is affected by ecological and behavioral factors at the individual, community, and regional levels.

Malaria prevention focuses on controlling the mosquito vector or reducing contact between humans and vectors. Predominant strategies include insecticide-treated bed nets (ITNs) and indoor residual spraying of insecticides (IRS). Environmental management is another option that is gaining support, particularly in light of growing resistance to insecticides and antimalarials (Lindsay & Birley, 2004). Utzinger et al. (2001) argue that despite a wide variety of efforts to combat malaria, including engineered malaria-resistant mosquitoes and new vaccines, these will take time and may not succeed. In the interim, the best option may be environmental management for vector control, including vegetation clearance and management of water bodies (e.g., modification of river boundaries, drainage of swamps, reduction of standing water, and application of oil to open water bodies). Further support for environmental management comes from Keiser et al. (2005), who review 24 studies and find that environmental management decreases the malaria risk ratio substantially (88% reduction in the risk ratio for environmental modifications and 79.5% for human habitation modifications).

Malaria vaccines represent another prevention strategy that could prove very beneficial over the long run. Vaccine research has made substantial progress recently—one vaccine (RTS,S/AS02A) appears very promising—but an effective agent is unlikely to be available for widespread use for at least ten years (Greenwood et al. 2005).

Besides vector control and other preventative strategies, case management (treatment) is the other major plank in efforts to combat malaria. Indeed, prompt and effective treatment using chemophrophylaxis is widely recognized as the most cost-effective malaria control strategy (Goodman et al. 1999). Because the rate of infectious contact is critical in disease transmission, prompt individual treatment is an important form of population-level prevention (Wilson, 2001).

Despite the importance of disease treatment for both individuals and society, several important barriers impede effective treatment on a broad scale. First, people in endemic areas often lack access to treatment beyond inferior drugs. Second, accurate and consistent diagnosis is critical for successful treatment (Greenwood et al. 2005). Ideally, interventions should be predicated upon laboratory-based diagnosis involving some form of "bloodwork" through microscopy, dipstick, or test strip. Unfortunately, most individuals do not avail themselves of these tests and treatment is mostly limited to clinical or self-diagnosis. These diagnoses are often inaccurate because signs and symptoms of malaria are nonspecific and overlap with other febrile infectious diseases and because the subjective sensation of fever is unreliable. As a result, society engages in unnecessary and inappropriate treatment and drug use that can have toxic side effects, impose unnecessary costs for individuals and health systems, and increase parasitic resistance (Guerin et al. 2002).

Resistance of mosquitoes to insecticides is an additional barrier to malaria prevention.[1] Multiple economic factors may cause inappropriate use of drugs and pesticides, shortening the useful life of these substances and hindering long-term malaria prevention and treatment (Reed et al. 2002).

Finally, an essential ingredient of almost all prevention and treatment packages is local awareness of malaria-control alternatives. For example, high mortality from severe malaria (which can result in organ failure, cerebral malaria, and acute anemia) continues because patients arrive in an advanced state, although home or village-based rectal administration of artesunate is a promising approach (Guerin et al. 2002). Individuals can also minimize exposure to the vector by limiting activities in the early morning and evening hours, using repellents, and maintaining and using ITNs.

The public-health responses discussed in this section—vector control, case management, and vaccine development—represent the mainstream in malaria control [see for example the recently completed reviews by the Roll Back Malaria program (WHO & UNICEF, 2005) and the Working Group on Malaria (Teklehaimanot et al. 2005)]. These approaches are predominantly supply-side; for example, officials from national health ministries might identify, choose, and target an indoor residual spraying regimen in a place and time of their choice, rather than on the basis of household demand for and participation in such treatment. Such strategies gloss over the behavioral basis of malaria transmission, particularly the modifications and adaptations by individuals, households, and communities to their disease exposure, which in turn is affected by the natural and psychosocial environments (Pattanayak et al. 2006). Given that the host is not a passive agent in the "agent-host-environment" framework, the human ecology approach and the more recent eco-epidemiology framework are vital for understanding how humans modify and adapt to their environment, including their disease environment (Wessen, 1972; MacCormack, 1984; Parkes et al. 2003). The following review of the role of deforestation in malaria transmission seeks to establish the basis for this proposition.

Deforestation Impacts on Malaria

An ecological perspective on the life cycles of parasitic microorganisms and their associated infectious diseases is critical to understanding and controlling these diseases (Wilson et al. 1994; Wilson, 1995).[2] Moreover, infectious diseases are part of a larger human ecology in which "human social systems, economic activities, interactions with the environment, and lifestyles represent some of the key domains of interaction that affect infection and disease risk" (Wilson, 2001). Each environmental change, whether occurring as a natural phenomenon

[1] Resistance is more likely to emerge when background immunity is weak, parasite numbers in individuals are high, transmission is low, and insecticide and drug pressure is intense. *P. falciparum* has become variably resistant to all drug classes except the artemisinin derivatives.

[2] Our understanding of the ecological basis for disease dates back at least as far as Hippocrates' "On Airs, Waters, and Place," written in 400 BC.

or through human intervention, alters the ecological balance and context within which disease hosts, vectors, and parasites breed, develop, and transmit diseases (MacCormack, 1984; Parkes et al. 2003).

In general, vector-borne anthroponoses such as malaria are strongly affected by environmental factors influencing the abundance and survival of the vector. Indeed, Smith et al. (1999) attribute 70-90% of the risk of malaria to environmental factors. The variety and magnitude of environmental influences on malaria are enormous (Wilson, 2001). Abiotic elements such as precipitation and temperature affect the abundance of mosquito vectors and the development of parasites within the vectors. In addition, biotic factors operating through deforestation, agriculture, and housing construction may also influence vectorial capacity. Furthermore, the impact of deforestation and other land-use changes on temperature, precipitation, and vegetation reveals the interacting and correlated nature of these environmental influences.

While a number of anthropogenic land-use changes have the potential to affect the emergence, reemergence, and spread of infectious diseases, the relationship between deforestation and malaria is particularly important (Lindsay & Birley, 2004; Patz et al. 2004). As Patz et al. (2004) note, deforestation has accompanied increases in malaria in Africa, Asia, and Latin America. Widespread felling of trees is often a precursor to other important land-use changes such as agricultural expansion and intensification. Deforestation has also attracted substantial policy attention and innovation, with potential cross-effects on malaria control. While we recognize the importance of other processes—for example urbanization—in the evolution of malaria, we focus here primarily on deforestation. In particular, a review of the literature reveals five potential pathways through which forest management and deforestation can affect malaria infection and disease transmission (Walsh et al. 1993, Patz et al. 2000; Wilson, 2001; Molyneux, 2003; Patz et al., 2004).

First, deforestation changes the ecology of a disease vector and its options for hosts. Whereas primary growth forest floors tend to be heavily shaded and littered with a thick layer of organic matter that absorbs water and renders them quite acidic, cleared lands, generally more sunlit and on flat terrain, are prone to the formation of puddles with more neutral pH that can favor specific anopheline larvae development (Patz et al. 2000).[3]

Second, deforestation can affect climate at local, regional, and even global scales (through impacts on the global carbon cycle). Where the scale of deforestation is large, such as in the Amazon basin, the effects on temperature and moisture and, therefore, on vector habitats, could be quite significant (Wilson, 2001). Higher temperatures can increase the pace at which mosquitoes develop into adults, the frequency of their blood feeding, the rate at which parasites are acquired, and the incubation of the parasite within mosquitoes (Walsh et al. 1993). For example, deforestation and its related activities have produced new habitats for *Anopheles darlingi* mosquitoes and have been correlated with malaria epidemics in South America (Walsh et al. 1993). The different species complexes in Southeast Asia (*A. dirus, A. minimus, A balabacensis*) have been differently affected by forest clearance with varied impacts on malaria incidence (Walsh et al. 1993).

Third, deforestation is often just the first step in a chain of land-use changes. These modifications may involve agriculture and livestock, plantations, human settlement, forest regeneration, road construction, and water-control systems (i.e., dams, canals, irrigation systems, and reservoirs). Networks of irrigation ditches, canals and impoundments, as well as puddles from road construction, can improve vector habitats. Livestock can change vector ecology and vectorial capacity, influencing malaria-transmission patterns.[4] Rubber plantations in Malaysia encourage *A. maculatus*, whereas in Trinidad erythrina (with their bromeliads) encourage *A. bellator*. Insecticide use in subsequent agricultural activities on cleared land can increase vector resistance (Wilson, 2001).

Fourth, deforestation is accompanied by migration and other behavioral changes that may enhance the spread of malaria. In the case of gold mines in the Brazilian Amazon, migrants typically have little previous exposure and therefore lower immunity (Castilla & Sawyer, 1993). Moreover, migrants introduce additional complications associated with administering health services to transient populations—inadequate medical follow-up and possible side effects. Although incomplete treatment can relieve fever, the underlying malarial infection persists as the

[3] Molyneux (2003) points out that forest loss may also lead to the elimination of certain vectors that are specially adapted to the forest ecosystem, thereby decreasing the disease burden. The examples provided do not include malaria vectors, but this is at least theoretically possible.

[4] For example, certain Anopheles species are zoophilic, preferring to feed on livestock rather than humans. The introduction of livestock may thus decrease the human-malaria burden by providing mosquitoes with an alternative source of bloodmeals, a process known as zooprophylaxis. However, it is also possible that the introduction of livestock will expand vector abundance, leading to an increase in malaria. The direction of the effect is likely to vary, and depends on factors such as vector mortality, the ratio of humans to livestock, and proximity of livestock and humans to breeding sites (Saul, 2003).

migrant moves and potentially transmits the disease to other locations, often on the deforestation frontier.

Finally, ecosystem change such as deforestation can play a role in the antibiotic resistance that has become a major concern for several plasmodium species. Resistance evolves through processes of selection and evolution, responding to diverse factors such as extent of treatment, nature and site of antibiotic action, and genomic complexity of the parasite (Wilson, 2001). Greater virulence results from genetic changes that occur by chance mutation and subsequent drift of selection. While ecological change permeates the process, it is difficult to delineate the roles of specific forms of modification such as deforestation. However, it is possible that deforestation will increase the genetic diversity of parasite populations and increase the rate at which resistance evolves.

Reviewing Poverty, Deforestation, and Malaria Linkages

To this point, we have enumerated the potential benefits of reducing malaria incidence, choices for public-health interventions, and pathways by which deforestation may influence malaria. This is important within the cross-sectoral perspective we are advocating because deforestation is a significant development-policy issue (Deacon, 1994; Angelsen & Kaimowitz, 1999; Wunder 2001; Wood & Porro 2002; FAO 2005; Sunderlin et al. 2005; Sills & Pattanayak, 2006). Research on deforestation's causes and consequences, including income and poverty, has identified many public interventions to promote forest conservation (by slowing or reversing deforestation). Both forest and health policies ultimately aspire to enhance human welfare, as do policies that directly promote economic development of forest frontiers. Unfortunately, it is unclear which of these policies complement each other and which conflict because of the complex and dynamic relationship between deforestation, malaria, and poverty (see Wolman, 1995 for similar concerns). We consider it critical to incorporate deforestation and forest management into malaria research, not only because of the potential linkages enumerated earlier, but also because of linkages through the human causes and consequences of malaria and deforestation. Moreover, the tactics that can be employed to control malaria through forest conservation are clearly different from more traditional clinical, or even community medicine, approaches. We present four reasons why it is important to understand how malaria is linked to economic development via deforestation.

First, deforestation is not merely the exogenous (remote control) removal of forest cover (Patz et al. 2000). As discussed above, it is the beginning of an entire chain of activities, including forest clearing, farming, irrigating, livestock raising, and non-timber forest product collecting, that all have ecological (vector habitat) and behavioral (exposure and transmission) consequences for malaria.

Second, millions of rural households depend directly on a wide variety of forest products and services (Byron & Arnold, 1999). By lowering the natural wealth of local populations, deforestation can reduce household capacity to invest in health care and pay for malaria prevention and treatment. At the same time, deforestation may increase the wealth of other households that will then be better able to avoid and cure malaria.

Third, deforestation is an integral part of life and the landscape in many malaria-infested regions (Wilson, 2001; Donohue, 2003). Consequently, sustainable-forest management has become an important policy goal as donor agencies and local policymakers take a more integrated view of people in natural settings. The resulting land-cover changes, as well as modifications in how people interact with forests, have implications for malaria. Thus, conservation policies aimed at slowing deforestation affect malaria (Walsh et al. 1993; Ault, 1994; Taylor, 1997).

Finally, malaria and deforestation are central elements of the vicious poverty cycle in the rural areas of many developing countries. In simplistic terms, malaria could be considered to "cause" deforestation, because malaria can make people poorer and poverty can "cause" deforestation under some conditions. In reality, the linkages are, of course, more complex and context-specific. For example, Sawyer (1993) argues that high rates of malaria encourage men to work as day laborers (in logging or ranching) rather than establish family farms. This adaptive response allows women and children to live in towns with relatively lower malaria incidences. While it is often difficult to disentangle causality in such situations, it is clear, as Smith et al. (1999) observe, that "many of the most critical health problems in the world today cannot be solved without major improvement in environmental quality."

Empirical Evidence on Malaria-Deforestation-Poverty Links

The previous sections advanced several hypotheses regarding possible relationships among deforestation, malaria, and poverty. We now ask two important questions in light of these contentions. First, what do existing data tell us about deforestation-malaria-poverty linkages? We consider both macro-level and micro-scale analyses and draw lessons from each

Box 1 A Macro Viewpoint

We test the hypothesis that deforestation is a causal factor for malaria using country-level data on deforestation, malaria risk, and geographic and socio-economic control variables. Data on forest loss at the country level between 1990 and 2000 was collected from the World Development Indicators, while data on malaria risk at approximately the same time period (1994) and pre-determined covariates come from Kiszewksi et al. (2004). In total, 160 countries are represented, although several countries had missing values for one or more variables.

Nonparametric tests for correlation show that **change in forest cover is negatively associated with malaria risk** (ρ=-0.5). That is, countries that experience negative forest-cover change (deforestation) have higher rates of malaria. Regression analysis was used to probe this correlation in more detail to test whether or not the data could support a causal relationship between malaria and deforestation, controlling for other explanatory variables. In the most basic model involving no control variables, malaria risk is negatively correlated with deforestation rates. However, **once we control for a number of control variables in the analysis** (geographical location, quality of institutions, per capita income), **deforestation is no longer a significant correlate of malaria risk**. The one variable that is consistently significant in these analyses is the proportion of land area in the tropics. This variable's strong correlation between with both deforestation rates and malaria seems to be driving the observed correlation between malaria and deforestation. However, this should not be taken as proof that no such relationship exists. **This cross-sectional macro data set does not allow us to identify any causal link between deforestation and malaria**.

	Deforestation (P-value)	Controls	R Sq	N
Malaria risk	-0.07(<0.01)	--	0.06	160
Malaria risk	-0.01(>0.01)	location, gdp, institutions	0.67	142

of these perspectives. Second, what are the current gaps in our knowledge regarding the relationships among deforestation, malaria, and economic development, and what kinds of research could help to address these deficiencies?

Reviewing Evidence from Macro- and Micro-level Studies

Existing data sources provide two options for examining the links between deforestation, malaria, and economic development. The first approach uses national-level data to look for consistent macro-level correlations. For example, is deforestation consistently correlated with malaria risk, even when we control for other explanatory variables? Box 1 summarizes results from a macro-level analysis of the links between deforestation and malaria. Evaluation of these cross-national data suggests that malaria and deforestation are correlated at the national level. However, this relationship disappears when regression analyses include other factors such as tropical location.

A second approach uses individual- or household-level data to look for micro-level relationships. Such data sets allow us to identify detailed causal relationships in specific settings and to avoid some of the statistical problems (e.g., high correlation among explanatory variables, aggregation of local heterogeneity) that can undermine our ability to detect causal relationships. Box 2 summarizes the results from two micro-level studies of the links between ecosystem change and malaria in Indonesia. Both studies report a negative association between the extent of primary-forest and malaria. This finding is consistent with the notion that primary forest conservation can reduce malaria incidence.

Comparing macro- and micro-level studies reveals the benefits and drawbacks associated with each approach. Research on national-level data, particularly cross-sectional data, does not capture complex local and regional phenomena. Data available at the national level for several countries often lack sufficient detail to test more subtle hypotheses. For example, the two micro-level studies cited here found that more *primary* forest cover is associated with lower malaria rates, but the national-level data sets used in the macro-scale analysis record only *total* forest cover without distinguishing between primary and secondary forest. Conversely, micro-level studies are an excellent source of detailed knowledge about particular areas, but it is often hard to generalize these results across different settings. This observation is especially germane to informing policy decisions. The contrast between micro-level and macro-level studies, not unique to the deforestation-malaria problem, requires a multi-faceted research strategy that optimizes the relative advantages of each type of study.

Knowledge Gaps

Despite the previously described emerging body of knowledge about the economic and ecological causes and consequences of malaria, our understanding of these complex issues remains incomplete and inadequate (McMichael et al. 1998; Lindsay & Birley, 2004; Patz et al. 2004; Wilcox & Colwell, 2005). In particular, no study has comprehensively related deforestation to malaria incidence and burden by analyzing a longitudinal (panel) data set. Panel data allow the researcher to combine the best features of cross-sectional and time-series analysis while being able to control for population characteristics,

Box 2 A Micro Perspective

Malaria is highly contextual, with incidence and transmission depending on local conditions, perturbations, and catastrophes. Thus, **individual-level multi-factor research** is perhaps best suited to incorporate the diversity and heterogeneity of the ecological, epidemiological, and economic phenomena surrounding malaria. Two recent micro-level studies from rural Indonesia provide examples of this kind of research, and reveal linkages between deforestation and malaria.

In remote areas of developing countries, people's lives are closely intertwined with the condition of the natural environment particularly in rural areas that lack hospitals, doctors, and other public services. A household-production framework (Berman et al., 1994) can be used to specify econometric models to evaluate the links between ecosystem change and the incidence of malaria. Data from a survey of households residing near protected areas in Flores and Siberut Islands in eastern and western Indonesia are to estimate multivariate logit regression models. These models test the correlations between the forest protection and malaria, controlling for individual, household and community characteristics. The Flores case study focuses on child malaria (Pattanayak et al. 2005) and the Siberut case study focuses on adults (Ginwalla et al. 2005). In both cases the results indicate **statistically significant correlations between village-level forest protection and the incidence of malaria—**the extent of primary forest is negatively associated with malaria. Other significant factors related to malaria include gender, care giver's age, household wealth and house quality, village area and elevation, and level of public-health infrastructure. The statistically significant correlation between the forest-cover variables and child-malaria rates suggest that **forest protection may offer health benefits to nearby communities**.

	Primary forest (P-value)	Secondary forest (P-value)	Controls	Pseud RSq	N
Siberut (adults)	-(<0.01)	+(>0.10)	demographic, SES, physiographic	0.20	501
Ruteng (under 5)	-(<0.10)	+(<0.05)	demographic, SES, physiographic, public health	0.15	337

temporal dynamics, and unobservable variables to rigorously test causal relationships.

We believe that an interdisciplinary approach integrating economics, epidemiology, and ecology could address many of the knowledge gaps distilled below.

- Malaria is highly contextual, with incidence and transmission depending on local conditions, perturbations, and catastrophes. Any attempts to evaluate the relationship between forest conditions and malaria should adopt an individual-level, multi-factor approach to incorporate the diversity and heterogeneity of the ecological, epidemiological, and economic phenomena surrounding malaria incidence in particular locations. Nevertheless, the modeling of heterogeneity and diversity seems to be the exception rather than the rule in research on malaria's behavioral dimensions.
- The incomplete understanding of the human ecology of malaria is exemplified by the insufficient and partial modeling of behaviors—at societal, community, household, and individual levels—including a wide variety of observable and unobservable activities related to exposure, prevention, and treatment. Behavioral response is complex, and mechanistic behavioral models do not fully account for human responses to changing ecological and economic conditions. In particular, typical cost-of-illness estimates based on lost productivity ignore behavioral response altogether and thereby grossly under represent socio-economic impacts on individuals and households.
- Policy evaluations of malaria control have typically overlooked the full range of ecological factors in parasite life cycles. Several aspects of malaria, such as acquired immunity, vectorial and parasitic resistance, child development, and cumulative well being, involve long gestation periods. As far as we have discerned, no existing study fully incorporates these dynamic processes or measures the long-term benefits of malaria control.
- Forests are one of the primary ecological factors influencing malaria transmission. Yet, there is only a thin empirical literature on malaria in forest regions, at least in terms of research that considers socio-economic factors, including behaviors. Most critically, to date no research has comprehensively considered the role of forests in contributing goods and services and thereby changing household and individual wealth.
- Malaria control is an example of a real-world program that produces non-random (non-experimental) data with the associated problems of reliable inferences and conclusions. Evaluation science has made significant strides in data-collection and analysis methods that can address the concerns of heterogeneity, diversity, and dynamics (see, e.g., Singer, 1989; Ezzati et al. 2005). Unfortunately, malaria-control evaluations seem not to have fully incorporated this methodological gain into relevant analyses, and few long-term field studies have collected repeated cross-sectional, cohort, and/or panel data

on malaria's social and behavioral dimensions that could complement classical laboratory experiments.

Building a Comprehensive Strategy to Link Research and Policy

This paper highlights the need for further exploration of the complex relationships linking malaria, deforestation, and poverty. Understanding these relationships is critical for informing policies to decrease the burden of malaria, protect forest resources, and promote economic development. We propose that a carefully designed, integrated approach linking research and policy can address this need and, over time, lead to improved knowledge and outcomes. In particular, we contend that an overarching decision-analysis framework can facilitate both policy-relevant research and evidence-based policymaking.

A Decision-Analysis Framework

Decision analysis provides a framework for evaluating the factors that influence malaria and informing choices among different policy options (Kramer et al. 2006). The general approach underlying decision analysis involves mapping out a set of relationships to show how policy decisions interact with factors outside of the decision maker's control to generate a set of (potentially interrelated) outcomes (Clemen, 1996). In this case, decision makers must choose a set of policies affecting malaria, deforestation, and poverty. While these three kinds of policies are usually viewed separately, we emphasize the need to consider them simultaneously, as has been advocated in sustainability science (Kates et al. 2001), eco-epidemiology (Parkes et al. 2003), and human ecology (MacCormack, 1984). The policies implemented will interact with several factors outside of the decision makers' control to produce a joint set of malaria, deforestation, and poverty outcomes.

The decision-analysis framework provides the basis for an integrated and dynamic strategy linking research and policy. Figure 3 depicts this strategy visually and shows how the framework, research, and policymaking interact, with each drawing lessons from and providing inputs to the other two.

Policy-Relevant Research

The process of developing a preliminary decision-analysis framework will highlight gaps in our understanding of the relationships between malaria, deforestation, and poverty. Such an approach will also help us to set a research agenda that could remedy these deficiencies and better inform policy choices. The framework should reflect the collective initial understanding of the "knowns" and "unknowns" by a team of ecologists, economists, and epidemiologists. While this paper identifies some potential pathways, more work is needed to generate plausible and testable hypotheses and to suggest the variables for inclusion in testable models. Meta-analysis and literature review are two important tools for developing the decision-analysis framework and identifying key hypotheses (see, e.g., Eisele et al. 2000).[5]

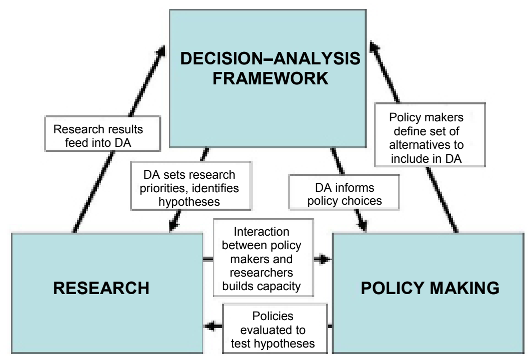

Figure 3 A comprehensive strategy to link research and policy

After constructing the initial decision-analysis framework and identifying key hypotheses, the next step is formulating empirical strategies to test these hypotheses. These strategies must address two interrelated issues: data collection and analytical methods.

The decision-analysis framework identifies which outcomes are of interest, as well as the various causal and confounding factors generating these outcomes. In this context, outcomes include indicators of health, wealth, and environmental quality. Extent of forest cover and forest condition are among the key explanatory variables. Other variables include socioeconomic status, demographic composition, environmental quality, health status, and public-health policy. The challenge in empirical work is to identify robust measures of these variables and to separate independent and dependent variables. The multiple channels for feedback between malaria, deforestation, and poverty suggest that these variables would be dependent in some specifications and independent in

[5] Meta-analyses can be structured and effective mechanisms for identifying gaps in the literature (Stanley, 2001). When the phenomenon or process is similar enough across the studies, meta-analysis is also helpful in generating hypotheses. In addition to meta-analysis of all empirical studies on the economic and environmental determinants of malaria incidence in forest regions, the decision-analysis framework can benefit from a more general review of different relevant bodies of literature, including socio-economic evaluation of disease-control policies (Singer, 1989; Ezzati et al. 2005) and ecology of infectious diseases (Wilson et al. 1994; Wilson, 2001).

other specifications and data sets. Although researchers can employ an array of sophisticated techniques to remedy defects in available data, clearly "prevention" in the form of careful data collection is superior to "cure" in the form of *ad hoc* statistical fixes (Heckman et al. 1999). Longitudinal data sets—and particularly panel data sets—are key to addressing at least three critical issues in the types of research proposed here: heterogeneity, endogeneity, and dynamics or mobility (Cebu Study Team, 1992; Ezzati et al. 2005). Data should ideally be collected at several scales, ranging from individual-level health and demographic data, to household-level economic information, to community- and regional-level environmental statistics and policy factors. Geographical information systems (GIS) can integrate data layers across space and time (Jacquez, 2000).

To ensure that the empirical work is policy relevant, it is critical to collect data on both the "treated" (participants in a clearly defined program or policy) and comparable "controls" (non-participants that represent the counterfactual scenario). Given that deforestation and diseases are potentially large-scale phenomena, it is important to consider ways to minimize contagion bias and/or measure "macro effects of treatments" on the controls or nonparticipants (Miguel & Kremer, 2004).

The goal of data analysis is to disentangle the effects that different mixes of health and forest policies, different target groups, and different environmental settings have on people's health and wealth. This calls for a range of parametric, non-parametric, and semi-parametric methods. Key lessons for empirical evaluations can be gleaned from Ravallion (in press). There are many parameters of interest in evaluating deforestation impacts on malaria and poverty, partly because of the heterogeneity of impacts. For this reason, analysts should use a variety of comparison groups and estimation methods and should highlight and explain the differences that emerge from the multiple approaches.

Because the prospective research program begins with the policy environment, results from these studies will provide parameter estimates that can be fed into the decision-analysis model to help identify optimal policies. The availability of better estimates related to policy outcomes will improve the confidence of decision makers in their choices. In addition to facilitating more informed policies, the experience of working with researchers and using decision-analysis tools can play an important capacity-building role.

Conclusion

The foregoing account describes the burden that malaria places on human development, provides preliminary empirical evidence on the role of deforestation as a causal factor, and proposes a framework for a transdisciplinary and policy-relevant research agenda. We argue that understanding the role of deforestation is essential to combating the growing global burden of malaria on human health and wealth. To this end, we propose decision analysis as the framework for linking research and policy to better comprehend and address this important challenge.

By bringing researchers and policymakers together, the decision-analysis framework will foster collaborations with important benefits for both sides. For researchers, coordinating with policymakers can improve the quality of their study designs and research results. For example, data collection can be timed to coincide with policy implementation, allowing "before" and "after" comparisons. Researchers can inform policymakers on how to integrate data collection and impact evaluation into policies. When resources are scarce and do not allow for immediate comprehensive policy implementation, some aspects may be randomized (e.g., the order in which regions receive the benefits of a policy that must be implemented incrementally). More fundamentally, collaboration between policymakers and researchers should lead to clearly stated, well-defined, and consistently implemented rules governing policy implementation. Any of these collaborative outcomes would facilitate testing hypotheses and identifying the effects of different interventions. Working with policymakers also gives researchers a sense of what matters "on the ground" by helping them to identify key variables and to build more policy-relevant models and analyses.

From a resource-allocation standpoint, the infrastructure for performing and disseminating this type of multi-disciplinary research should be developed in countries where the malaria burden is most pronounced. International organizations can foster the capacity for this work through in-depth technical assistance and training that provide individualized assistance to specific stakeholders such as local researchers, national policymakers, local government officials, and nongovernmental organizations. In general, a well-designed research program will allow researchers in developing countries to build skills in meta-analysis, cross-disciplinary research, publication for scientific peers and policymakers, and proposal-writing for long-term funding.

The proposals put forth here respond to several recommendations of the Working Group on Land Use Change and Disease Emergence as outlined in Patz et al. (2004). These include developing a conceptual model that links land-use and public-health policy; promoting research on deforestation and infectious disease; engaging in health-impact modeling; developing location-specific decision-support tools; implementing research and policy programs; and assessing and addressing trade-offs among environment, health, and development. The issues we raise, and the comprehensive research and policy strategy we promote, clearly complement these goals and may be important in implementing the Working Group's recommendations. These efforts can, in combination, give public-health officials, environmental agencies, and economic policymakers a better chance of effectively countering the threat of malaria while also promoting better land use and forest management, thereby improving the condition of millions of people worldwide.

References

Angelsen, A. & Kaimowitz, D. 1999. Rethinking the causes of deforestation: lessons from economic models. *The World Bank Research Observer* 14(1):73–98.

Ault, S. 1994. Environmental management: a re-emerging vector control strategy. *American Journal of Tropical Medicine and Hygiene* 50(6 Supp):35–49.

Berkes, F. & Folke, C. 1998. Linking social and ecological systems for resilience and sustainability. In F. Berkes, J. Colding, & C. Folke (Eds.), *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience.* pp. 1–24. New York: Cambridge University Press.

Berman, P., Kendall, C., & Bhattacharyya, K. 1994. The household production of health: integrating social science perspectives on micro-level health determinants. *Social Science and Medicine* 38(2):205–215.

Bremen, J. 2001. The ears of the hippopotamus: manifestations, determinants, and estimates of the malaria burden. *American Journal of Tropical Medicine and Hygiene* 64(1–2 Supp):1–11.

Byron, N. & Arnold, M. 1999. What futures for the people of the tropical forests? *World Development* 27(5):789–805.

Castilla, R. & Sawyer, D. 1993. Malaria rates and fate: a socioeconomic study of malaria and Brazil. *Social Science and Medicin*e 37(9):1137–1145.

Cebu Study Team. 1992. A child health production function estimated from longitudinal data. *Journal of Development Economics* 38(2):323–351.

Clemen, R. 1996. *Making Hard Decisions*, *2nd Ed*. Belmont, CA: Duxbury Press.

Deacon, R. 1994. Deforestation and the rule of law in a cross-section of countries. *Land Economics* 70(4):414–430.

Donohue, M. 2003. Causes and health consequences of environmental degradation and social injustice. *Social Science and Medicine* 56(3):573–587.

Eisele, T., Macintyre, K., Eckert, E., Beier, J., & Killeen, G. 2000. *Evaluating malaria interventions in Africa: a review and assessment of recent research.* Chapel Hill, NC: MEASURE Evaluation.

Ezzati, M., Utzinger, J., Cairncross, S., Cohen, A., & Singer, B. 2005. Environmental risks in the developing world: exposure indicators for evaluating interventions, programmes, and policies. *Journal of Epidemiology and Community Health*. 59(1):15–22.

Food and Agriculture Organization (FAO). 2001. *Global Forest Resources Assessment 2000.* Forestry Paper No. 140. Rome: FAO.

Food and Agriculture Organization (FAO). 2005. *State of the World's Forests 2005*. Rome: FAO. http://www.fao.org/docrep/007/y5574e/y5574e00.htm.

Ginwalla, Z., Kramer, R., Conde, D., & Pattanayak, S. 2005 Forest cover and malaria on Siberut Island, Indonesia. Unpublished paper. Nicholas School of the Environment, Duke University.

Goodman, C., Coleman, P., & Mills, A. 1999. Cost-effectiveness of malaria control in sub-Saharan Africa. *The Lancet* 354(9176):378–85.

Greenwood, B., Bojang, K., Whitty, C., & Targett, G. 2005. Malaria. *The Lancet* 365(9469):1487–1498.

Guerin, P., Olliaro, P., Nosten, F., Druilhe, P., Laxminarayan, R., Binka, F., Kilama, W., Ford, N., & White, N. 2002. Malaria: current status of control, diagnosis, treatment, and a proposed agenda for research and development. *The Lancet Infectious Diseases* 2(9):564–73.

Gunderson, L. & Holling, C. 2002. *Panarchy: Understanding Transformations in Human and Natural Systems*. Washington, DC: Island Press

Heckman, J., LaLonde, R., & Smith, J. 1999. The economics and econometrics of active labor market programs. In O. Ashenfelter & D. Card (Eds.), *Handbook of Labor Economics*. pp. 1865–2097. Amsterdam: North Holland.

Hutubessy, R., Bendib, L., & Evans, D. 2001. Critical issues in the economic evaluation of interventions against communicable diseases. *Acta Tropica* 78(3):191–206.

Jacquez, G. 2000. Spatial analysis in epidemiology: nascent science or a failure of GIS? *Journal of Geographical Systems* 2(1):91–97.

Kates, R., Clark, W., Corell, R., Hall, J., Jaeger, C., Lowe, I., McCarthy, J., Schellnhuber, H., Bolin, B., Dickson, N., Faucheux, S., Gallopin, G., Grubler, A., Huntley, B., Jager, J., Jodha, N., Kasperson, R., Mabogunje, A., Matson, P., & Mooney, H. 2001. Sustainability science. *Science* 292 (5517):641–642.

Kaufman, J. & Poole, C. 2000 Looking back on ''causal thinking in the health sciences.'' *Annual Review of Public Health* 21: 101–119.

Keiser, J., Singer, B., & Utzinger, J. 2005. Reducing the burden of malaria in different eco-epidemiological settings with environmental management: a systematic review. *The Lancet Infectious Diseases* 5(11):695–708.

Kiszewski, A., Mellinger, A., Spielman, A., Sachs, J., Malaney, P., & Sachs, S. 2004. A global index of the stability of malaria transmission. *American Journal of Tropical Medicine and Hygiene* 70(5):486–498.

Kramer, R., Dickinson, K., Anderson, R., Fowler, V., Miranda, M., Mutero, C., Saterson, K., & Weiner, J. 2006. Using Decision Analysis to Improve Malaria Control Decision Making. Unpublished Paper. Nicholas School of the Environment, Duke University.

Lindsay, S. & Birley, M. 2004. Rural development and malaria control in Sub-Saharan Africa. *EcoHealth* 1(2):129–137.

MacCormack, C. 1984. Human ecology and behavior in malaria control in tropical Africa. *Bulletin of the World Health Organization* 62(Supp):81–87.

McMichael, A., Patz, J., & Krovats, S. 1998. Impacts of global environmental change on future health and health care in tropical countries. *British Medical Bulletin* 54(2):475–488.

Miguel, E. & Kremer, M. 2004. Worms: identifying impacts on education and health in the presence of treatment externalities. *Econometrica* 72(1):159–217.

Molyneux, D. 2003. Climate change and tropical disease: common themes in changing vector-borne disease scenarios. *Transactions of the Royal Society of Tropical Medicine and Hygiene* 97:129–132.

Parkes, M., Panelli, R., & Weinstein, P. 2003. Converging paradigms for environmental health theory and practice. *Environmental Health Perspectives* 111(5):669–675.

Pattanayak, S., Corey, C., Lau, Y., & Kramer, R. 2005. *Conservation and Health: A Microeconomic Study of Forest Protection and Child Malaria in Flores, Indonesia.* RTI Working Paper *05_05*. Research Triangle Park, NC: Research Triangle Institute.

Pattanayak, S., Poulos, C., Jones, K., Yang, J., & Van Houtven, G. 2006. *Economics of Environmental Epidemiology*. RTI Working Paper *06_04*. Research Triangle Park, NC: Research Triangle Institute.

Patz, J., Graczyk, T., Geller, N., & Vittor, A. 2000. Effects of environmental change on emerging parasitic diseases. *International Journal for Parasitology* 30(12–13):1395–1405.

Patz, J., Daszak, P., Tabor, G., Aguirre, A., Pearl, M., Epstein, J., Wolfe, N., Kilpatrick, A., Foufopoulos, J., Molyneux, D., & Bradley, D. 2004. Unhealthy landscapes: policy recommendations on land use change and infectious disease emergence. *Environmental Health Perspectives* 112(10):1092–1098.

Ravallion, M. (in press). Evaluating anti-poverty programs. In R. Evenson & T. Schultz (Eds.), *Handbook of Agricultural Economics Volume 4.* Amsterdam: North Holland.

Reed, S., Laxminarayan, R., Black, D., & Sullivan, S. 2002. Economic issues and antibiotic resistance in the community. *The Annals of Pharmacotherapy* 36(1):148–54.

Sachs, J. & Malaney, P. 2002. The economic and social burden of malaria. *Nature* 415(6872):680–685.

Saul, A. 2003. Zooprophylaxis or zoopotentiation: the outcome of introducing animals on vector transmission is highly dependent on the mosquito mortality while searching. *Malaria Journal* 2:32.

Sawyer, D. 1993. Economic and social consequences of malaria in new colonization projects in Brazil. *Social Science and Medicine* 37(9):1131–1136.

Sills, E. & Pattanayak, S. 2006. Tropical tradeoffs: an economics perspective on tropical deforestation. In S. Spray & M. Moran (Eds.), *Tropical Deforestation.* pp. 103–128. Lanham, MD: Rowman & Littlefield.

Singer, B. 1989. Social science and the improvement of tropical disease control programs. *Annals of the New York Academy of Science* 569:275–287.

Smith, K., Corvalán, C., & Kjellstrom, T. 1999. How much global ill health is attributable to environmental factors? *Epidemiology* 10(5):573–584.

Stanley, T. 2001. Wheat from chaff: meta-analysis as quantitative literature review. *Journal of Economic Perspectives* 15(3): 131–150.

Sunderlin, W., Angelsen, A., Belcher, B., Burgers, P., Nasi, R., Santoso, L., & Wunder, S. 2005. Livelihoods, forests, and conservation in developing countries: an overview. *World Development* 33(9):1383–1402.

Taylor, D. 1997. Seeing the forests for more than the trees. *Environmental Health Perspectives* 105(11):1186–1191.

Teklehaimanot, A., Singer, B., Spielman, A., Tozan, Y., & Schapira, A. 2005. *Coming to Grips with Malaria in the New Millennium*. London: Earthscan.

Utzinger, J., Tozan, Y., & Singer, B. 2001. Efficacy and cost-effectiveness of environmental management for malaria control. *Tropical Medicine and International Health* 6(9):677–687.

Walsh, J., Molynneux, D., & Birley, M. 1993. Deforestation: effects on vector-borne disease. *Parasitology* 106(Supp):S55–S75.

Wessen, A. 1972. Human ecology and malaria. *American Journal of Tropical Medicine and Hygiene* 21(1):658–662.

WHO & UNICEF. 2005. *World Malaria Report 2005*. Roll Back Malaria Partnership. http://www.rbm.who.int/wmr2005/.

Wilcox, B. & Colwell, R. 2005. Emerging and reemerging infectious diseases: biocomplexity as an interdisciplinary paradigm. *EcoHealth* 2(4):244–257.

Wilson, M., R. Levins, & A. Spielman (Eds.). 1994. *Disease in Evolution: Global Changes and the Emergence of Infectious Disease*. New York: New York Academy of Sciences.

Wilson, M. 1995. Infectious diseases: an ecological perspective. *British Medical Journal* 311(7021):1681–1684.

Wilson, M. 2001. Ecology and infectious disease. In J. Aron & J. Patz (Eds.), *Ecosystem Change and Public Health.* pp. 285–291. Baltimore, MD: The Johns Hopkins University Press.

Wolman, R. 1995. Human and ecosystem health: management despite some incompatibility. *Ecosystem Health* 1:35–40.

Wood, C. & Porro, R. 2002. *Deforestation and Land Use in the Amazon*. Gainesville, FL: University Press of Florida.

World Health Organization (WHO). 2001. *Economic Costs of Malaria*. Roll Back Malaria InfoSheet #10. http://www.rbm.who.int/cmc_upload/0/000/015/363/RBMInfosheet_10.htm.

Wunder, S. 2001. Poverty alleviation and tropical forests: what scope for synergies? *World Development* 29(11):1817–1833.

COMMUNITY ESSAY

Challenges for sustainability in cultures where regard for the future may not be present

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A concept of time depends upon both culture and linguistics, and one person's future may be another person's present. Temporal and spatial concepts are crucial to sustainability issues and a concept of "the future" may depend upon ethnicity, linguistic background, lifestyle, and life expectancy. Many currently threatened natural systems are in locations where the indigenous people have a linguistic and conceptual background very different from those in the so-called developed countries. One example is the Bajau people who live off the southeast coast of Sulawesi in Indonesia, close to highly endangered coral reefs. How can we connect the "future perspective" mismatch between Austronesian people like the Bajau and conservationists from developed countries who want to protect the reefs for future generations? Many challenges are ahead, not the least being a practical one of providing the right education for the Bajau to show how certain actions—for example, "no-take" fishing zones—can help achieve their aspirations. Perhaps even more important is the moral challenge of reassessing our own assumptions about worthwhile aspirations, about what is good for the Bajau—and similar people—and their rights and roles in determining the outcomes.

Time present and time past
Are both perhaps present in time future
And time future contained in time past.
If all time is eternally present
All time is unredeemable.

–T. S. Elliot, "Burnt Norton," *The Four Quartets*

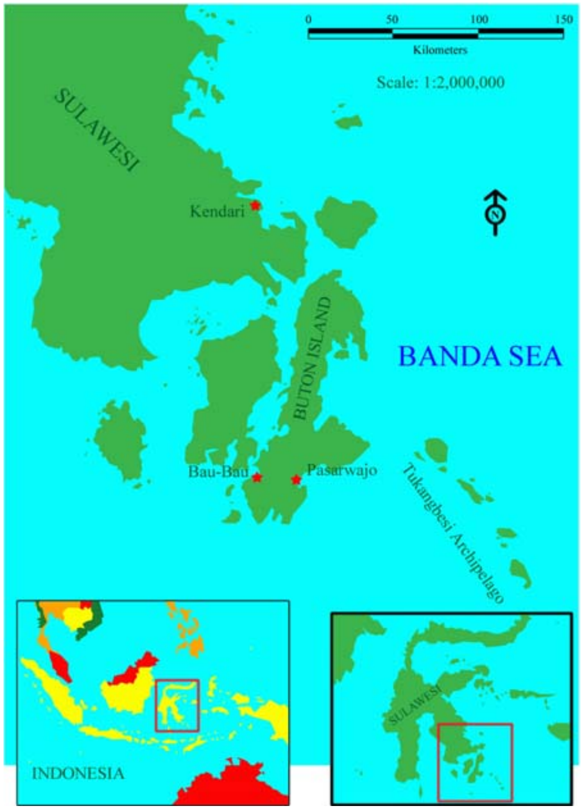
The Concise Oxford Dictionary defines the word "sustain" as "keep up adequately; keep from failing." The notion of time is central to a concept of sustainability, as to sustain something we need to nourish and nurture it and keep it from failing over a period of time. In the West, our vision of time enables us to discuss system sustainability, whether it is of a natural system, for example a rainforest or a coral reef, or a human-made system, such as the automobile industry. A future vision is central to sustainability.

Many currently threatened natural systems are situated where the indigenous people have a linguistic and conceptual background very different from our own. Not only do they have different language roots (see, e.g., Terrell, 2004; Chow et al. 2005), they have varying models for the concept of "the future" and "time," as is the case for the Suriname Maroons (Heemskerk, 2003). Other people with Austronesian languages, such as the Bajau, do not have a word for "future" as we understand it (Donohue, 1996). One goal of a "Western" approach to sustainability is to ensure that future generations have ample options (Tonn, 2004). This situation presents a mismatch in understanding and in application, with severe consequences for both sides, not to mention consequences for the ecosystems that need sustaining. This essay explores such an ecosystem, along with some of the challenges it poses and potential solutions.

One-third of all marine fish species and tens of thousands of other species are found in coral reefs, from which 6 million tons of fish are caught annually. This activity level not only provides an income for commercial fishing fleets, but also supports numerous communities that rely on local fish stocks for nutrition. The annual global economic value of coral reefs has been estimated to be around US$375 billion (see, e.g., Cesar, 1996; Cesar et al. 1997). Modern reefs have existed for approximately 50 million years. How much longer the reefs can survive is often asked in the developed world, particularly as global warming, resort development, and other human endeavors are resulting in rapid reef degradation (Souter & Linden, 2005; Wilkinson et al. 2006). But artisanal fishers who live on the reefs may not understand the question, at least not as we might. Their vision of "the future" with respect to the reefs may be very short term, if it exists at all.

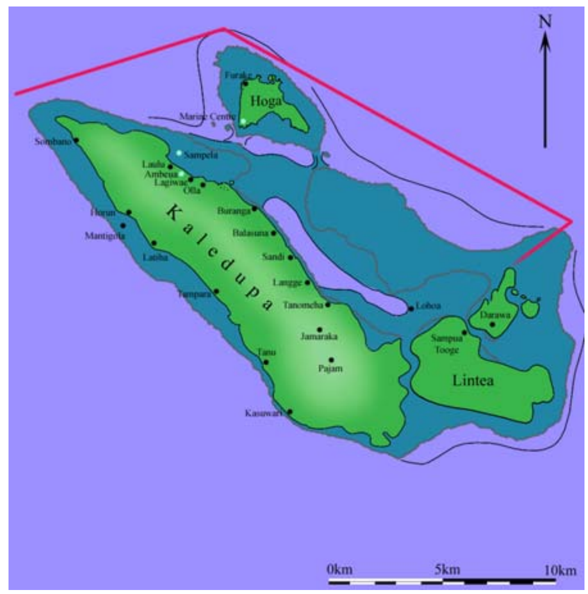
One example of this phenomenon is found in Indonesia's Wakatobi Marine National Park (Crabbe et al. 2004a; Crabbe et al. 2006), located in the Tukangbesi archipelago, southeast of Sulawesi, as shown in

Map 1. Between the islands of Hoga and Kaledupa there is a Bajau community at Sampela (see Map 2).



Map 1 Southeast Sulawesi and the Tukangbesi Archipelago. The islands shown in Map 2 are in the archipelago south east of the island of Sulawesi.

The term "Bajau" is applied to a variety of seafaring peoples whose scattered settlements extend across the South China Sea. Known variously as Badjaw, Bajau, Sama di Laut, or Bajo, they are one of three major groups of nomadic, or formerly nomadic, maritime foraging societies native to Insular Southeast Asia. Also in this group are the Moken/Moklen, of the Mergui Archipelago and coastal Thailand, and the Orang Laut, of the Riau archipelago. The Sama-Bajau are the largest of the three groups, and arguably the most widely dispersed ethno-linguistic group indigenous to the region. Groups of Sama-Bajau speakers can be found over an area of 1.25 million square miles, from the southern Philippines to Borneo and Sulawesi, reaching as far as Flores and the Moluccas (Sather, 1997). The Sama di Laut typically maintain a primarily subsistence-based economy, exploiting some of the world's richest marine ecosystems—the unique combination of coral reefs and mangrove forests that characterize littoral Southeast Asia. They have traditionally lived in houseboats, migrating between "moorages" over a wide area according to fishing conditions, political situations, and kin obligations. Nomadic-maritime groups in the Philippines use the autonym Sama (Pallesen, 1985). If they need to differentiate themselves from genetically-related shore-dwelling peoples, they call themselves "Sama di Laut" or "Sama of the sea" (Nimmo, 2001). The term "Bajau" appears to be of Indonesian origin and refers to boat-dwelling peoples; this identifier has been adopted throughout Borneo as a generic term for the whole Sama-Bajau linguistic group. The Philippine government distinguishes in its census between the shore Sama and the nomadic "Bajau."



Map 2 Islands and settlements in the Tukangbesi archipelago, south east of Sulawesi in Indonesia (see Map 1). The Bajau community at Sampela is situated between the islands of Hoga and Kaledupa in the Wakatobi Marine National Park.

Why these groups appear to lack a "Western" appreciation of the future is unclear. It may be that something inherent in maritime nomadism has contributed to their truncated view. Nothing in their recent history, apart from their day-to-day dependence upon artisanal fishing and their short life expectancy, seems to have contributed to their apparent short-termism.

The local Bajau village in Wakatobi, Sampela consists of approximately 200 houses located on top of stilts embedded into fine sand flats and is home to roughly 1,300 people. The Bajau people depend on the sand flats and coral-reef community for food. This particular community has existed only since about the middle of the twentieth century and all the dwellings are built upon coral that has been mined from the area. Coral mining—the use of corals taken out of the reefs by mechanical means and used as building materials—is a real problem for the region's reefs. There is currently a lively trade in the corals mined on the reef for use as building materials, both in the village and on the large neighboring island of Kaledupa. Mining is responsible for the nearly complete loss of massive corals that settled and began to grow before 1950. The Bajau village is built almost entirely on foundations of coral mined from the area nearest to the settlement (Figure 1). Based on economic considerations alone, the local community needs to replace coral construction with cement and concrete. A case study in Lombok, Indonesia estimated that for every US$10 net profit gained through coral mining, there was a net loss of US$245 through diminishment of fisheries, coast protection, and tourism (Cesar, 1996).

The Bajau village experiences high energy storm waves during December through February and the loss of the protective coral barrier will have severe consequences for the erosion rates of the sand flats upon which the village is situated. To retain the reef wall's integrity, and to reduce the amount of sediment depositing on the reef, the sandflats should be biostabilized, for example, by the promotion of seagrass communities. Curtailing the mining of non-branching corals will also help to protect the reef environment and provide a barrier to dissipate storm-wave energy (Crabbe et al. 2004a; Crabbe & Smith, 2005, 2006).

Figure 1 The Bajau village of Sampela built upon corals from local reefs mined by the villagers (photo by M. James C. Crabbe).

Bomb fishing, also a major source of coral degradation, is estimated to destroy 3.75% of the live coral cover each year in some areas (Pet-Soede et al. 1999). Fishers use chemical bombs made from fertilizer and kerosene or diesel fuel to kill or stun fish, making them easy to collect. While bomb fishing may provide quick profits, the practice destroys the structure of the coral reef and the habitats that maintain fish populations.

Cyanide fishing is another technique that wreaks havoc on coral reefs. Divers crush cyanide tablets into plastic-squirt bottles of seawater and puff the solution at fish on coral heads. Systematic scientific testing of cyanide's impact on reefs is scant, but the chemical can undoubtedly kill corals, and its toxic effects on fish are well known. The fish often hide in crevices, obliging the divers to pry and hammer the reefs apart to collect their stunned prey. Cyanide fishing also poses health risks to fishers through accidental exposure to the poison and careless use of often shoddy compressed-air diving gear by untrained divers. These destructive fishing practices are used by members of the Bajau community, as well by Indonesians from outside the local Bajau area (Crabbe et al. 2004b).

Despite their islands' designation as a marine protected area, and despite financial help from the World Wildlife Fund and the World Bank, the Bajau are trapped in a "development cycle" of increased aspirations, lack of capital, dependence on wage labor, and natural-resource depletion with the increased degradation of the coral reefs. Their plight is mirrored by peoples with similar linguistic backgrounds who lack a future perspective in sustainability and who populate threatened ecosystems (Huang & Tanangkingsing, 2005; Gelcich et al. 2005). New local opportunities are urgently needed if these communities are to remain intact (Shepherd & Terry, 2004). Basic services, such as sanitation, healthcare, and education, are rare. The infant mortality rate can be so high that many mothers cannot remember the number of children they have lost, and the average number of years in school is a mere four (Sather, 1997).

Alternative income sources are desperately needed for such people, especially in instances where the conservation concerns of well-meaning Westerners disrupt local livelihoods by creating "no-take" zones and other protected jurisdictions. Alternative income schemes, such as agar agar farming, are succeeding in some areas (Nimmo, 2001). Farming of agar and other seaweed species in aquatic environments provide useful sources of foods, gels, and medicinal products. Although organizing such ventures can be difficult given that these communities do not function as a corporate group, the strength of kin networks suggests a possible starting point, with some persuasion from political leaders required. Credit associations and other cooperative schemes, deployed through women's social and kin networks, have had considerable success in other parts of the world, notably West Africa (Nimmo, 2001). Social networks among the Bajau and similar peoples do, indeed, tend to be organized around the women (given the preference for uxorilocality and endogamy within kin clusters), and women have traditionally controlled household finances, so this sort of strategy holds promise.[1]

Education is one approach to try to connect the "future perspective" mismatch between conservationists from developed countries and Austronesian people such as the Bajau. However, there is a dilemma. What is the point of stressing the importance of education and more responsive policymaking if the real problem is a poorly developed cultural conception for long-term futures?

This situation presents us with two challenges, one practical and one moral. The practical challenge is to provide the Bajau with information at the appropriate level to demonstrate how certain actions—for example, "no-take" fishing zones—can help to achieve their aspirations. This intervention would need to address local economic and social concerns about the reefs, particularly their costs and benefits, and the range of options presently available.

The moral challenge is to reassess our own assumptions regarding people such as the Bajau and to acknowledge their rights and capacity for self-determination. We need to hold in greater esteem the diversity of social contributions that local people can make, and to maintain respect for a wider range of cultural values that can legitimately inform life choices about coral-reef sustainability.

A draconian approach would be to seek to alter the aspirations of people such as the Bajau in the interests of both the wider community and the wider economy. Is doing so not to treat the people who hold such values as the means rather than as the ends? Who is to say that we should seek to change their ecologically destructive practices as a way of protecting them from themselves? Should we not respect their own rights and capacities to determine their own fate? The role of indigenous communities in natural-resource management is complex and easily oversimplified, as it has been with the Bajau of the Tukangbesi archipelago. The questions "Whose aspirations? Whose achievements?" will continue to resonate in issues of sustainability and conservation. And we do not have much time. For people around the world who rely on coral reefs for their livelihoods, anthropogenic effects are degrading the local resource base at an alarming rate.

[1] Uxorilocality refers to the practice whereby a man goes to live with his spouse in her village, often with her family, upon marriage. Endogamy is the custom of marrying within a specific social group, class, or ethnicity.

Time past and time future
Allow but a little consciousness

–T. S. Elliot, "Little Gidding," *The Four Quartets*

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References

Cesar, H. 1996. *Economic analysis of Indonesian coral reefs*. Washington DC: World Bank.

Cesar, H, Lundin, C., Bettencourt, S., & Dixon, J. 1997. Indonesian coral reefs: An economic analysis of a precious but threatened resource. *Ambio* 26(6):345–350.

Chow, R., Caeiro, J., Chen, S., Garcia-Bertrand, R., & Herrera, R. 2005. Genetic characteristics of four Austronesian-speaking populations. *Journal of Human Genetics* 50(11):550–559.

Crabbe, M. & Smith, D. 2005. Sediment impacts on growth rates of *Acropora* and *Porites* corals from fringing reefs of Sulawesi, Indonesia. *Coral Reefs* 24(3):437–441.

Crabbe, M. & Smith, D. 2006. Modelling variations in corallite morphology of *Galaxea fascicularis* coral colonies with depth and light on coastal fringing reefs in the Wakatobi Marine National Park (S.E. Sulawesi, Indonesia). *Computational Biology and Chemistry* 30(2):155–159.

Crabbe, M., Karaviotis, S., & Smith, D. 2004a. Preliminary comparison of three coral reef sites in the Wakatobi Marine National Park (S.E. Sulawesi, Indonesia): Estimated recruitment dates compared with Discovery Bay, Jamaica. *Bulletin of Marine Science* 74(2):469–476.

Crabbe, M., Karaviotis, S., & Smith, D. 2004b. Monitoring growth of hard corals as performance indicators for coral reefs. *Journal of Biological Education* 38(3):113–117.

Crabbe, M., Wilson, M., & Smith, D. 2006. Quaternary corals from reefs in the Wakatobi Marine National Park, SE Sulawesi, Indonesia show similar growth rates to modern corals from the same area. *Journal of Quaternary Science* Published Online: 12 May 2006

Donohue, M. 1996. A symmetrical Austronesian language. *Language* 72(4):782–793.

Gelcich, S, Edwards-Jones, G., & Kaiser, M. 2005. Importance of attitudinal differences among artisanal fishers toward co-management and conservation of marine resources. *Conservation Biology* 19(3):865–875.

Heemskerk, M. 2003. Scenarios in anthropology: Reflections on possible futures of the Suriname Maroons. *Futures* 35(9):931–949.

Huang, S. & Tanangkingsing, M. 2005. Reference to motion events in six Western Austronesian languages: Toward a semantic typology. *Oceanic Linguistics* 44(2):307–340.

Nimmo, H. 2001. *Magosaha: An Ethnography of the Tawi-Tawi Sama Dilaut.* Quezon City: Ateneo de Manila University Press.

Pallesen, A. 1985. Culture contact and language convergence. *Linguistic Society of the Philippines, Special Monograph Issue* 24. Manila: Linguistic Society of the Philippines.

Pet-Soede, C., Machiels, M., Stam, M., & Van Densen, W. 1999. Trends in an Indonesian coastal fishery based on catch and effort statistics and implications for the perception of the state of the stocks by fisheries officials. *Fisheries Research* 42(1):41–56.

Sather, C. 1997. *The Bajau Lau: Adaptation, history, and fate in a maritime fishing society of Southeastern Sabah.* New York: Oxford University Press.

Shepherd, S. & Terry, A. 2004. The role of indigenous communities in natural resource management – the Bajau of the Tukangbesi archipelago, Indonesia. *Geography* 89(3):204–213.

Souter, D. & O. Lindén (Eds.). 2005. *Coral Reef Degradation in the Indian Ocean (CORDIO) Status Report*. Kalmar, Sweden: University of Kalmar.

Terrell, J. 2004. 'Austronesia' and the great Austronesian migration. *World Archaeology* 36(4):586–590.

Tonn, B. 2004. Integrated 1000-year planning. *Futures* 36(1):91–109.

Wilkinson, C., D. Souter, & J. Goldberg. (Eds.). 2006. *Status of coral reefs in Tsunami affected countries: 2005*. Australia: AIMS Press.