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Hawai'i's Mountain-to-Sea Ecosystems: Social–Ecological Microcosms for Sustainability Science and Practice

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Abstract: There is an urgent need to develop the underlying theory and principles of "sustainability science," based on an understanding of the fundamental interactions between nature and humans. This requires a new research and education paradigm that embraces biocomplexity, integrates the physical, biological, and social sciences, and uses a coupled, human–natural systems approach. An initiative aligned with this paradigm and approach, and centered on the Hawaiian Island's unique mountain-to-sea ecosystems, is developing at the University of Hawai'i. These ecosystems, extending from upland tropical forests to the fringing coral reefs, correspond to the roughly wedge-shaped catchments, traditionally called *ahupua'a* in the Hawaiian language. Despite the collapse of the *ahupua'a* system and, tragically, the Native Hawaiian population, its legacy of ecological and cultural stewardship remains. This legacy, and the potential of these ecosystems as microcosms for addressing the core questions of sustainability science, has provided the impetus for a growing number of projects employing a social–ecological systems perspective. An overview of three projects that employ a "learning community" approach and cultural stewardship perspective inspired by the *ahupua'a* system is provided. These include the Ecosystems Thrust Area of Hawai'i EPSCoR, a U.S. National Science Foundation research infrastructure program, focused on ecosystem research and monitoring activities; a sustainability curriculum program, *Mālama I Ka 'Āina*, of the College of Education; and a project that builds on programs of the Division of Ecology and Health and its affiliated Asia-Pacific Center for Infectious Disease Ecology, linking ecosystem resilience and infectious diseases.

Key words: sustainability, ecosystems, environmental sensors, ecological monitoring, disease ecology, resilience

INTRODUCTION

The quality of life for present and future generations depends on the development and adoption of new research paradigms that integrate the physical, biological, and social sciences (Wilcox and Colwell, 2005). This research is required to provide the new insights and the fundamental knowledge needed to address the wide range of issues associated with ecosystems and their relationship to human health and well-being. The recent rapid rise in oil prices,

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Table 1. Core Questions of Sustainability Science

1. How can the dynamic interactions between nature and society—including lags and inertia—be better incorporated into emerging models and conceptualizations that integrate the Earth system, human development, and sustainability?
2. How are long-term trends in environment and development, including consumption and population, reshaping nature–society interactions in ways relevant to sustainability?
3. What determines the vulnerability or resilience of the nature–society system in particular kinds of places and for particular types of ecosystems and human livelihoods?
4. Can scientifically meaningful "limits" or "boundaries" be defined that would provide effective warning of conditions beyond which the nature–society systems incur a significantly increased risk of serious degradation?
5. What systems of incentive structures—including markets, rules, norms, and scientific information—can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?
6. How can today's operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?
7. How can today's relatively independent activities of research planning, monitoring, assessment, and decision support be better integrated into systems for adaptive management and societal learning?

increased frequency of extreme weather events, and reanalysis of data adding to the preponderance of evidence of increasing global temperature are a stark reminder of the physical and biological limits on global society. These signs demonstrate an urgent need for the development of a new science as the basis for understanding the fundamental character of interactions between nature and society; what is being called "sustainability science" (Kates et al., 2001).

A series of core questions help define "sustainability science" and its research agenda in a global context (Table 1). As Kates et al. (2001) describe, these problems require advances in our ability to address such issues as the behavior of complex, self-organizing systems as "coupled human–natural systems" (see also Berkes et al., 2003; Adger et al., 2005). While sustainability as a global challenge addresses a wide range of social and environmental issues—-from income and health disparities to energy and natural resources use (e.g., UN Millennium Development Goals, http://www.unmillenniumproject.org)—these arguably are reducible to the problem of resilience in the transformations of human and natural systems (Gunderson and Holling, 2002), and what Berkes et al. (2003) refer to as "building capacity to adapt to change." Fundamental to this argument is the distinction between the reductionistic view of resilience (*engineering resilience*) and the holistic view (*ecosystem resilience*). As described by Holling and Gunderson (2002), *engineering resilience* is measured in terms of the resistance to disturbance and speed of return to equilibrium. *Ecosystem resilience* is measured by the magnitude of disturbance that can be absorbed before the system changes in structure (e.g., collapses). It is a nonequilibrium concept consistent with the notion, now well accepted in physics and by an increasing number of social and natural scientists, that living systems are far-from-equilibrium systems shifting between different stable states (metastability). Following this thinking, sustainable relationships between people and nature, at the core of sustainability, require emphasis on *ecosystem resilience* as defined here. This requires a shift in the predominant policy and management philosophy of top-down, command and control, to an adaptive approach that embraces the complexity, nonlinearity, and inherent unpredictability of social–ecological systems.

How is this theoretical perspective being translated into practical, "on-the-ground" solutions to sustainability problems? Finding solutions, including building resilience in human and natural systems, requires collaboration not only among scientific disciplines but also of scientists and society at large. This will require new ways of knowing and learning that both transcend disciplinary boundaries within the scientific community, and form "learning communities" not confined to academia. These communities necessarily include people who interact directly with natural systems, particularly those with knowledge based on first-hand experience and cultural transmission of information, as well as others who interact indirectly—whether policy makers, resource managers, or the public. These learning communities provide the basis for resilience underlying the adaptive approach described above.

A vision to develop such communities, along with research and monitoring activities addressing sustainability issues, began emerging during the past decade centered on Hawai‘i’s unique physical, biological, and social circumstances. At the core of this vision, and conceptualized by many in Hawai‘i as microcosms for sustainability research and practice, are the distinct mountain-to-sea ecosystems of the Main Hawaiian Islands. These areas, whose land boundaries typically are defined by a watershed or catchment corresponding to a single natural drainage system, are called *ahupua‘a* in the Hawaiian language. However, in their traditional conception, they extend from forested uplands to the fringing reefs, and served as the core administrative and management units that formed the basis of Hawai‘i’s traditional natural resource and food production system (Berkes, 1999). Today, they are the focus of ecological and cultural restoration initiatives of local communities, as well as outdoor laboratories for studying ecosystem and human health linkages, to investigate, for example, the mechanisms by which anthropogenic environmental change alters biodiversity and ecological functions. They are microcosms in the sense that the dynamics of human–natural system transformations, which normally are characterized in sustainability studies and projections on a regional and global scale (e.g., NAS, 1999; Turner et al., 1990), have occurred—and are occurring—here on a spatial scale of approximately $1/10^6$ this size.

In this profile, we describe the development of three major projects that have adopted this Hawai‘i mountain-to-sea perspective to address contemporary challenges in sustainability science and education. This is only a partial view and snapshot in time of current efforts in Hawai‘i addressing important components of sustainability. These particular projects will evolve, merge with, and spin-off others which will become their successors. However, they are illustrative of the direction being taken, motivated by and organized around the *ahupua‘a* concept and historical legacy, and employing a learning community approach.

The Vision: A Natural and Cultural Historic Imperative

The natural and cultural history of the Hawaiian Islands, their geographic location bridging the Americas, the Pacific, and Asia, and the science and education infrastructure that has developed make Hawai‘i a unique place for research and training in sustainability science. Hawai‘i is home to over 10,000 unique life forms, offering scientists opportunities to test classical theories of evolution and population biology and to formulate new paradigms concerning the adaptability of organisms to ever-changing environmental conditions. However, island ecosystems are extremely fragile and Hawai‘i’s vulnerability is clearly demonstrated by the extinction crisis of its native biota. The islands thus provide an unrivaled opportunity to develop cutting edge research in the processes involved in the maintenance of biodiversity and ecosystem function.

Yet this research, and the conservation and management prescriptions based on it, cannot be confined to the natural sciences. To be useful it must be contextualized—culturally, politically, and economically. As a start, the present circumstances, as well as future prospects, are largely the result of what may best be described as a dramatic social–ecological systems transformation that has taken place during the past two centuries since initial European contact. This transformation actually represents the collective transformation of hundreds of *ahupua‘a*, each of which have followed different trajectories. Despite the homogenizing influence of Western colonization, the distinctive socio-cultural and ecological character of each *ahupua‘a* is still apparent today.

As alluded to above, *ahupua‘a* were conceived and operated by pre-contact Hawaiian society as the basis of an intricate system of land division demonstrated in part by the historic map of the Island of Hawai‘i shown in Figure 1. Not shown by the map, but clearly marked in higher resolution maps from this period and before, are the *ahupua‘a* boundaries as they extend out to the fringing reefs and sometimes beyond, encompassing the marine resource production and management component. Also not shown are the numerous management zones corresponding mainly to the ecology of the landscape (and seascape) used to guide production and stewardship practices. A sense of this complexity is illustrated in Figure 2A.

These systems and their traditional settlements are now the sites of modern rural and urban communities, in some cases small cities (as represented in Fig. 2B), most of which bear the names of their historic *ahupua‘a*. While the land use/cover and natural drainage systems of nearly all of them have been significantly altered, as can be seen in Figure 3, their original distinguishing landscape features remain visibly intact. Historically, the use and management of each *ahupua‘a* was tailored to the specific ecological patterns and processes of its mountain-to-sea ecosystem, which

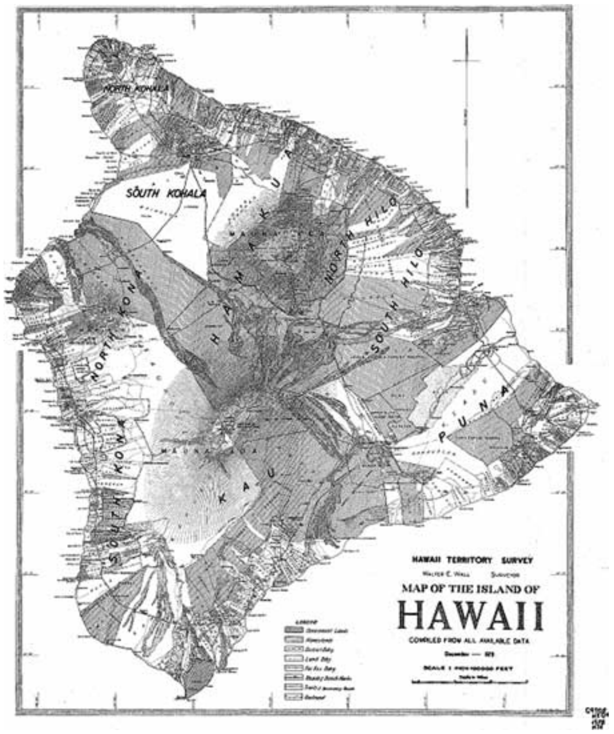

Figure 1. Territorial survey map of the Island of Hawai'i, the largest of the six Main Hawaiian Islands, compiled in 1928. It shows the boundaries and names of land units that had evolved over the centuries prior to European contact. Most of these units, which are of varying size but are generally wedge-shaped and ring the island, are *ahupua'a.* The largest land division (there were other intermediate and even smaller divisions) was the *moku-o-loko* (district—literally: interior island), which on this island bore the names *Kohala, Kona, Ka'ū, Hāmākua Puna, and Hilo.*

differ substantially particularly between the leeward and windward (*ko'olau*) sides of an island. The collective skills, knowledge, and wisdom required to optimally exploit an *ahupua'a*, were developed to a level difficult to appreciate today, as documented at length by Handy et al. (1972). For example, about 200 varieties of taro were cultivated, many undoubtedly purposely bred to exploit the different soils and weather regimes. Taro pond fields and their irrigation systems, and inland and shore fishponds, constructed with thousands of coral or volcanic stones and boulders, maximized food production. Native lore and historical accounts specific to every *ahupua'a* still conveyed by oral traditions and contained in numerous published and unpublished written documents, represent a rich legacy of traditional ecological knowledge. This knowledge, with its associated values and perspectives, and Hawai'i's land use history as viewed through the historical decline of the *ahupua'a* system, are highly relevant to the current challenge of integrating human needs and environmental stewardship in these ecosystems.

Hawai'i's Cultural and Land History

At the time of first significant European contact with the early voyages of Cook, Vancouver, and missionaries (1778–1820), a thriving nation state had developed, based on the *ahupua'a* system, supporting a population of around 400,000. This population density was possible as a result of a sophisticated knowledge of the land (and sea) and how to manage its resources, along with a deep cultural attachment that had developed along with the *ahupua'a* system. However, the administration of the chiefdoms, and eventually Hawai'i as a nation state, were built on the *ahupua'a* as the basic land division. So the *ahupua'a* was at the heart of the political economy as well as the culture. Thus, from a social–ecological systems perspective, the collapse of the *ahupua'a* system—through changes in land tenure, the shift to a monetary economy, and a series of plagues introduced during the early period of European contact (Table 2)—and that of the Hawaiian nation and its native population, were not distinct historical phenomena. This was a single, self-reinforcing process, involving numerous negative feedback loops within and between both the human and natural components of the system.

This chronology, shown in Table 2, marked by specific events that prompted or facilitated the collapse, is associated with a succession of other dominant production modes and land uses after the *ahupua'a* system declined. This is represented in the transformation from what had been a highly integrated and diversified agriculture–aquaculture system to a Western-influenced intense resource extraction and largely monocrop (sugarcane or pineapples) plantation agriculture system (from approximately 1850 to 1970), and ultimately to today's mixed rural-urban-industrial land use and a largely tourism and defense-based economy. This human–natural system dynamic not only can be described culturally and socio-politically (as demonstrated by the events in Table 2), but also in terms of the characteristic landscape and drainage basin changes illustrated by Figures 2 and 3. These have precipitated other changes in ecological functions affecting the hydrologic regime of mountain-to-sea ecosystems in Hawai'i that have specific human health and safety implications discussed further below.

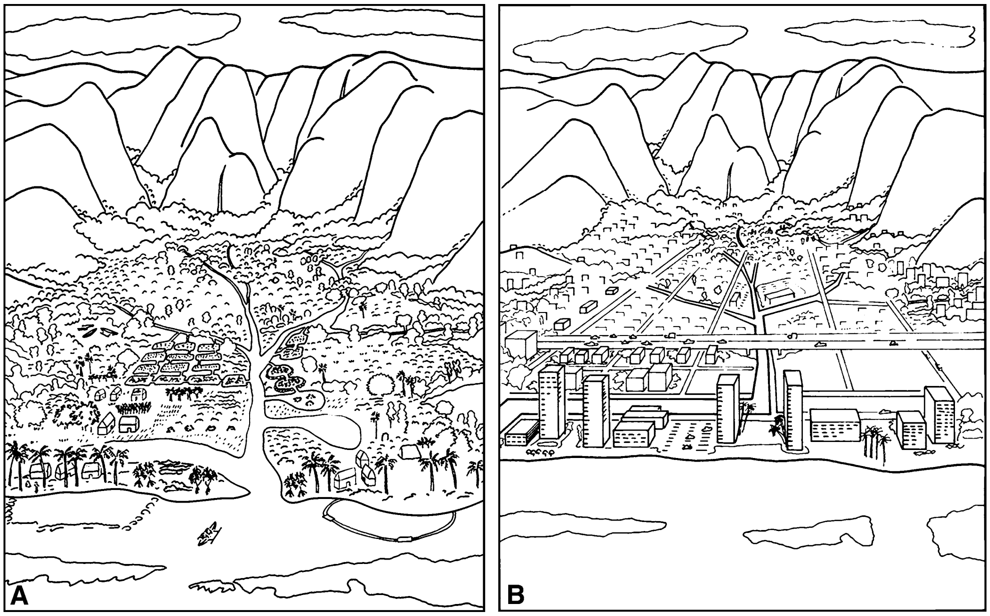

Figure 2. Drawings of a typical pre-contact and a modern *ahupua'a* and corresponding mountain-to-sea ecosystems. **A:** The Hawaiian *ahupua'a* system before, and up to the time of, first European contact. The pond fields (*lo'i*) in which taro were cultivated (that can be seen in the drawing being fed by streams) and shore fish ponds were the most prominent features and productive components of these highly diversified agriculture–aquaculture systems. **B:** The same *ahupua'a* or mountain-to-sea ecosystem as seen today, representative of one of Hawai'i's urbanized settlements. Presently, the steep montane zones shown are characteristically covered by forest or woodland formations consisting of mostly nonnative plants and animals (conserved as rainwater recharge zones).

Figure 3. Photographs showing the two extremes of settlement types characteristic of Hawai'i's modern day mountain-to-sea ecosystems. Aerial view of Hawai'i's most urbanized settlement, the city of Honolulu (Island of O'ahu) **(A),** and a typical concrete segment of a stream draining the Alawai-Waikīkī catchment **(B).** Aerial view of a typical rural settlement **(C),** and a natural stream channel **(D).**

Table 2. Chronology of Hawai'i's Social–Ecological Transformation[a]

I. First introduction of Western technology, values, and organisms	
1778	Arrival of James Cook
1793	Introduction of cattle and sheep
1804	*'Ōku'u*—Epidemic of cholera
II. Breakdown of traditional Hawaiian cultural authority	
1810	Trade (sandalwood/Western crops)
1819	*'Ai noa* (breaking of *kapu*, destruction of temples and formal religious system)
1820	Arrival of missionaries
1826	Epidemics
III. Shift in the dominant production mode and system of land tenure	
1830–1835	Introduction of plantation agriculture
1838	Epidemic of mumps
1844	Epidemic of colds
1848	*Māhele 'Āina* (the Land Division)
1848–1849	Epidemic of measles
1850	Royal Patent Grants
1852–1853	Epidemic of smallpox
1857	Epidemic
1862	Commission on Boundaries
1865	Epidemic of leprosy
IV. Transfer of sovereignty, property, and access rights	
1875–1884	Treaty of Reciprocity
1893	Overthrow of Hawaiian Monarchy
1898	Annexation by U.S.
1900	U.S. Territory
1920	Hawaiian Homes Act
1959	Plebiscite/Hawai'i Statehood
V. Cultural renaissance	
1970	Land restoration rights movement begins (e.g., Kalama Valley, Protect Kaho'olawe 'Ohana) and "poor health" status of Native Hawaiians gain formal recognition
1976	Transpacific navigation of the replica Polynesian voyaging canoe, Hōkūle'a
1978	Constitutional Convention (recognizes Hawaiian and English as official languages; founding of Office of Hawaiian Affairs)
1980	First Hawaiian language immersion program for schools
1988	U.S. Congress passes the Native Hawai'i Health Care Improvement Act

[a]The headings from I to V and events under each indicate the major historical phases associated with the collapse of the traditional *ahupua'a* system, the Native Hawaiian population, and ultimately the overthrow of the Hawaiian Monarchy and the annexation of the Hawaiian Islands by the U.S. The events under "V. Cultural Renaissance," were largely motivated and informed by a resurgence of appreciation of the cultural values and knowledge tied to *ahupua'a*. The information in the table is drawn from a variety of historical references, including, but not limited to: Eyewitness accounts (1800–1900) recorded in the journals of missionaries and foreign visitors, and Hawaiian newspapers (both English and Hawaiian); the writings (1830s–1870s) of native historians, David Malo (1951), John Papa I'i (1959), Samuel Kamakau (1961); and records and documents of the Hawaiian Kingdom (e.g., *Māhele 'Āina*, and Health and Educational Departments).

Current Issues and Efforts

A cultural renaissance catalyzed by a series of events in the 1970s (Table 2) refocused attention on the *ahupua'a* as many of Hawai'i's residents sought to restore indigenous cultural values and practices, e.g., taro farming and fishpond management, relevant to sustainability and stewardship. Thus, as a result of their correspondence to historic *ahupua'a*, Hawai'i's mountain-to-sea ecosystems, with their visibly distinguishable topography, cultural records, and place-based communities, present excellent opportunities for participatory research and practice in areas of ecosystem research and education, restoration, and community health.

Hawai'i faces numerous challenges requiring mountain-to-sea ecosystem focused "participatory action research" that have only recently been adequately documented or officially recognized. Nearly all of its streams are presently categorized as impaired (Koch et al., 2004), nonpoint source runoff and season sewage spills pollute its coastal waters (NRDC, 2005), and along with overfishing (NOAA and NMFS, 2005), threaten the already significantly degraded coral reef ecosystem in the Main Hawaiian Islands (Pandolfi et al., 2005). There is increasing awareness of these problems, and the threat to the capacity of the mountain-to-sea ecosystems to continue to provide the very environmental services that sustain Hawai'i's economic and human health. A number of research or education programs are developing that focus on key issues related to sustainability within the mountain-to-sea context. In addition to several especially prominent Hawai'i-based institutions with such projects (Table 3), three interrelated

Table 3. Hawai'i-based Research Institutions and Centers Developing Research Projects in the Context of Hawai'i's Mountain-to-Sea Ecosystems

Hawai'i Biodiversity & Mapping Program (HBMP)
A research program within the Center for Conservation Research and Training (CCRT), Pacific Biosciences Research Center (PBRC) of the University of Hawai'i. The program includes the Marine GAP project (http://hbmp.hawaii.edu/mgap/) which is compiling a database of all available information about species in Hawai'i's near-shore waters which will be easily linked with terrestrial information and utilized for research and conservation planning (Principal Investigators: Kenneth Kaneshiro and Barbara Gibson).
Hawai'i Institute of Marine Biology (HIMB)
A unit within University of Hawai'i's School of Oceans & Earth Science & Technology (SOEST) that conducts laboratory and field marine biology research throughout the Hawaiian Islands from its base on Coconut Island in Kāne'ohe Bay in Windward O'ahu (http://www.hawaii.edu/HIMB/). HIMB is developing a new program with an ecosystem focus investigating the links between coral bleaching, coral diseases, and environmental stressors related coastal development and global climate change (Principal Investigators: Jo-Ann Leong and Greta Aeby).
Kewalo Marine Laboratory
A laboratory of PBRC with research projects focusing primarily on the developmental biology, ecology, and evolution of marine invertebrates of Hawaiian near-shore marine environment (http://www.kewalo.hawaii.edu/). A major current focus includes the investigation of the relationship of land-based activities coastal coral reefs (Principal Investigator: Robert Richmond).
University of Hawai'i Center for Oceans and Human Health
One of four Centers on Ocean and Human Health (COHH) funded by the National Science Foundation (NSF) and the National Institute of Environmental Health Sciences (NIEHS). Jointly administered by SOEST and the John A. Burns School of Medicine (JABSOM), one of the Center's research cores projects, *Microbial Pathogens in Tropical Coastal Water*, is using an ecosystem approach to determine risk and prevent waterborne diseases (http://www.prcmb.hawaii.edu/p2.asp) (Co-Principal Investigator: Roger Fujioka).
Coral Reef Ecosystem Division (CRED)
A unit within the U.S. National Oceanographic and Atmospheric Administration's National Marine Fisheries Service (http://www.nmfs.hawaii.edu/), CRED conducts near real-time and long-term monitoring, modeling, and reporting of biological and physical environmental conditions which influence coral reef ecosystems. The unit is developing plans to expand its capacity to monitor nutrients and human pathogenic organisms (Director: Rusty Brainard).
Asia-Pacific Institute for Tropical Medicine and Infectious Diseases (APITMID)
A new research institute of JABSOM with five centers (http://apitmid.hawaii.edu/). The Institute's Pacific Center for Emerging Infectious Diseases Research (PCEIDR) (Director: Richard Yanagihara) and the Asia-Pacific Center for Infectious Disease Ecology (Director: Bruce Wilcox) are developing emerging infectious diseases research projects in Hawai'i's mountain-to-sea ecosystems (Director: Duane Gubler).

projects employing the approach to sustainability science described above are underway at the University of Hawai'i.

Key Projects Addressing Sustainability Science

Ecosystem Science—Hawaiian Style

Hawai'i EPSCoR (Experimental Program to Stimulate Competitive Research) (http://www.epscor.hawaii.edu/about.asp) is a National Science Foundation (NSF) program that has been instrumental in laying the foundation for an ecosystem science project (EPSCoR Ecosystems Thrust Area) centered on the mountain-to-sea approach. Along with conventional field research and monitoring methods, this program is establishing a network of field sampling stations and state-of-the-art wireless sensors to enable long-term ecological monitoring that will be used to assess ecosystem health. As an example of the program, the Waipā Project encompasses the *ahupua'a* of Waipā, Lumaha'i, Wainiha, and Limahuli (http://www.epscor.hawaii.edu/project/pubWebProj.asp?id=6&memID=11). These four *ahupua'a* represent adjoining natural catchment systems influencing the health of the coral reef ecosystem within and surrounding Hanalei Bay. Research and monitoring objectives include predicting habitat deterioration and changes in biodiversity due to climatic change or alien species; identifying patterns of environmental change that may lead to emergence of disease vectors such as mosquitoes or increased incidence of leptospirosis; and monitoring conditions affecting populations of rare and endangered species.

The significant accomplishments of the Hawaiʻi EPSCoR program have been critical to the University's selection as the base of the Pacific Island node as part of the U.S. National Ecological Observatory Network (NEON). This will be the first national ecological measurement and observation system in the world designed both to answer regional- to continental-scale scientific questions and to have the interdisciplinary participation necessary to achieve credible ecological forecasting and prediction (http://www.neon-inc.org). The development of wireless sensor networks and environmental monitoring capability on regional scales during the first 3 years of the Hawaiʻi EPSCoR program have resulted in a scalable, GPS-enabled, radio frequency-based system, deployable across complex landscapes at selected monitoring locations. The ability to accumulate real-time environmental data in order to "forecast" ecological change is the essence of the NEON enterprise.

NEON's Learning Community Initiative, which seeks to facilitate collaborative research and learning among scientists, educators, and interest-based communities (e.g., managers, government agencies, citizens, teachers, students) is an important component. NEON's learning community vision is based on the philosophy that the scientific and engineering breakthroughs required to deal with humanity's expanding impacts on earth's environmental systems will, in large measure, depend upon advances in environmental research and education that allow people to "discover, learn, teach, collaborate, disseminate, access, and preserve place-based knowledge" (NCAR and NSF, 2003). Together with the infrastructure provided by Hawaiʻi EPSCoR, NEON will be particularly important for integrated monitoring and assessment for reporting and adaptive management necessary to address core sustainability science questions 6 and 7 in Table 1. This represents a notable change from the conventional view of ecological monitoring focused on biophysical indicators. In effect, it integrates monitoring of biophysical and socio-cultural indicators of resilience.

Education, Sustainability Science, and Hawaiian Culture

The *Mālama I Ka ʻĀina* program funded by awards from the U.S. Department of Education (DOE) and based at the College of Education focuses on sustainability science curriculum and teacher development (http://malama.hawaii.edu). Its mission is to improve and expand the education of Hawaiʻi's children by providing professional development, and developing and disseminating science curricular materials based on understanding ways in which traditional Hawaiians effectively managed the environment for sustainability.

Mālama I Ka ʻĀina explicitly addresses worldviews embedded in cultural narratives, the key stories and myths that reveal core values and representation of reality. Modernity, exemplified in the narrative of progress achieved by man's dominion over nature, is foundational to Western culture. However, it is associated with "disembedding," the separation of social relationships from local contexts and "distanciation," the spreading out of social relations over space and time (Gerber, 2001). Davidson-Hunt and Berkes (2003) note "the separation of nature and society became a foundational principle of Western thought and provided the organizational structure for academic departments" (p 53). The *Kumulipo*, the Hawaiian narrative of creation, that holds people and the universe linked as family, represents the opposite principle. The *ahupuaʻa* system oriented Hawaiians in their relationships to others and local resources. Exchange of goods and services, including marriage within the *ahupuaʻa*, developed interdependence, self-sufficiency, and sense of place associated with deep environmental knowledge (Abbott, 1992). The high value placed on stewardship is captured in the proverb, *He aliʻi ka ʻāina; he kauwā ke kanaka* ("The land is a chief; man is its servant") (Pukui, 1983).

Mālama I Ka ʻĀina and *Pīkoi Ke Kaula Kualena*, two curriculum development projects funded by the U.S. DOE have prepared 100 kindergarten-to-secondary teachers since 2000 to develop place- and standards-based curricula focused on environmental literacy. Place-based learning from a Hawaiian cultural perspective connects indigenous knowledge, values, and practices to ecosystem studies. Site Teachers on the Islands of Oʻahu, Maui, Hawaiʻi, Kauaʻi, and Molokaʻi lead learning communities inclusive of indigenous practitioners, scientists, and kindergarten-to-university students in projects on ecological restoration, bioremediation, mapping, and monitoring. A social–ecological system perspective and a "human-in-ecosystem model" (Davidson-Hunt and Berkes, 2003) incorporating indigenous Hawaiian understandings of the relationships of humans and nature is used to develop science curricula oriented to real world issues in particular places.

Site Teachers also form the hub of local networks of *makaʻāinana* ("eyes of the land"), the traditional name for those who worked on and watched over the land. These networks serve as communities of practice (Wenger, 1998) spanning institutions and knowledge bases with the goal of studying, monitoring, and addressing environmental issues. They also enable research scientists to access local knowledge and research sites, and lead the community-based projects. Together, these have begun to develop into learning communities as the catalysts for building the capacity to adapt to change, thus creating the institutional resilience required for sustainability.

This sustainability science education program will be particularly important in helping address the social and human livelihoods dimension of core sustainability science question 3, as well as contributing to addressing core questions 5 and 7 in Table 1.

Linking Ecosystem and Human Health

A significant opportunity to advance understanding and provide training focused on the linkages between ecosystem and human health began with the establishment of a Division of Ecology and Health within the University of Hawai'i's medical school. The mission includes fostering interdisciplinary research and training focused on problems in Hawai'i and the Pacific Islands, and integrating "eco-health principles" within the medical curricula (Wilcox and Kasuya, 2004). Its programs also employ an *ahupua'a* and mountain-to-sea ecosystem approach involving a learning community philosophy with three foci: the connection between community, culture, and health in place-based communities; natural resources conservation, traditional ecological knowledge, and the links to public health; and the ecology of infectious diseases. One project focused on infectious disease, but that has involved the integration of elements of the other two research and training foci, is particularly illustrative of sustainability science, and will be elaborated on here.

Mountain-to-Sea Ecosystem and Waterborne Pathogens—Leptospirosis as a Model System

A basic challenge for this initiative has been to develop operational definitions of sustainability and working models expressing these definitions that yield testable hypotheses. Ecosystem resilience, measured as the capacity of a mountain-to-sea ecosystem to ameliorate the effects of disturbance on the emergence of human pathogens, is being employed as one such operational definition in this project. A model developed around this idea grew out of the Division of Ecology and Health's role in establishing a "sister" unit focused on infectious diseases, the Asia-Pacific Center for Infectious Disease Ecology. Operating under the Asia-Pacific Institute for Tropical Medicine and Infectious Diseases has enabled researchers to begin to integrate ongoing ecological, ethnographic, as well as historical and contemporary cultural and land use studies of *ahupua'a* with infectious disease research. The results have contributed to the development of a novel model for waterborne emerging infectious diseases that shows particular promise toward understanding as well as controlling leptospirosis (Fig. 4).

Discussed in detail by Vinetz et al. (2005), the model has become part of a larger investigation of what is a globally significant emerging infectious disease. This mountain-to-sea initiative project on leptospirosis helped provide the catalyst for this transdisciplinary research model as well as providing the potential for advancing sustainability science. A particularly important aspect is its community-based participatory approach that views leptospirosis as more than a medical problem. As perceived by local taro farmers and Native Hawaiian groups, it is also a problem of the health of *ahupua'a*, important to maintaining Hawai'i's cultural heritage, influenced by the historical and present day cultural, political, and economic factors. Taking a social–ecological systems perspective, and building on the infrastructure created by Hawai'i EPSCoR including developing partnerships with Native Hawaiian and other community groups, the project has been able to expand. This expansion includes the integration of conventional field studies of pathogen reservoir mammals, environmental monitoring instrumentation, and new molecular methods for *Leptospira* detection in the environment. Notably, local knowledge and community partnerships, essential to the field research component, led to the working model shown in Figure 4 and the overarching hypothesis being used to develop the research and prevention programs.

Using a coupled, human–natural systems approach, a model based on ecosystem resilience was developed. This model attempts to explain host infection prevalence and human disease risk as a function of the interaction of the environmental changes associated with the development (e.g., unplanned urbanization) of catchments or watersheds with rainfall variability (e.g., extreme rainfall events). High rainfall events and associated floods are hypothesized to play a dual role. Floods (and droughts) promote elevated host infection prevalence, thus in-

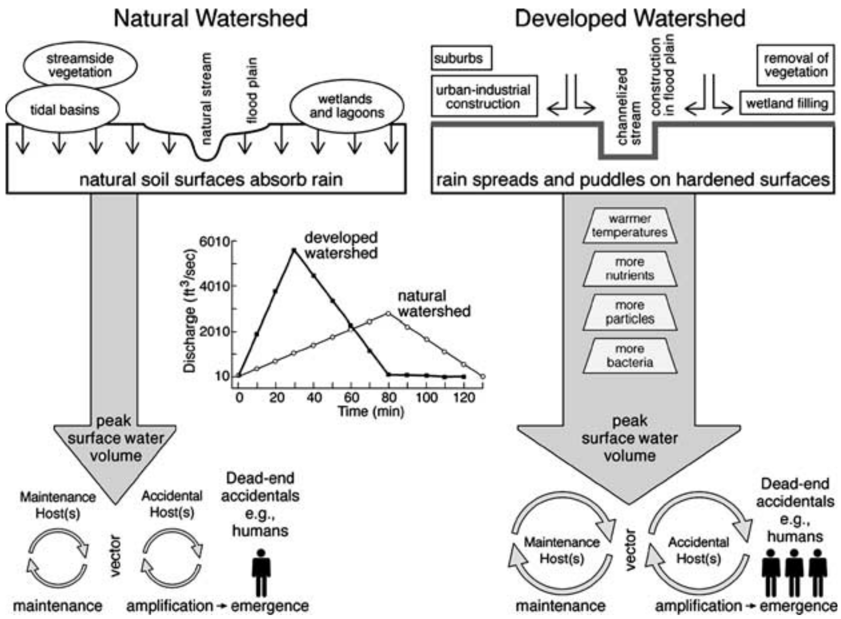

Figure 4. Model of the relationship of catchment hydroecology and the effects of drainage basin development on leptospirosis prevalence in Hawai'i's mountain-to-sea ecosystems [based on Wilcox et al., manuscript in preparation]. The top of the figure shows the hydroecological features and channel cross sections of a "natural watershed" (left) and "developed watershed" (right). The arrows pointing downward from each cross section represent the volume of surface water runoff that occurs following storm events. These flows normally carry microbes, such as pathogenic *Leptospira* bacteria shed in the urine of mammals, as well as other "contaminants" and sediments mobilized due to the interaction of rainfall and soil or other surfaces. The bottom of the figure illustrates the maintenance and amplification transmission cycles for pathogenic *Leptospira*, for both domestic animals and humans ("accidental" hosts). The larger circles representing the transmission cycles (bottom right) in the "developed watershed" represent increased rates of pathogen transmission and infection prevalence. In the center is a hydrograph generated using a standard hydrological equation with rainfall and runoff data for the upper Mānoa drainage on the Island of O'ahu. (The peak discharges for the two scenarios were computed using the Rational Method [SCS, 1985]. The hydrograph was developed using the Resources Conservation Natural Service Triangular Unit Hydrograph Method [SCS, 1986]. The design storm event for rainfall input was derived using the Rainfall Frequency Study for O'ahu [Giambelluca et al., 1984]. The watershed area was derived from a raster GIS shape file downloaded from the State of Hawai'i Department of Economic, Business and Tourism website [http://www.hawaii.gov/dbedt/gis/], and computed using ArcGIS.)

creased concentration of pathogenic *Leptospira* in the soil, and ultimately, surface waters. Reservoir species contaminate soil, streams, pools, and puddles by shedding *Leptospira* in their urine. Secondarily, flood events not only promote amplification of the maintenance hosts transmission cycle, when *Leptospira* contaminated water results in outbreaks in domestic species (e.g., cattle, horses, dogs, etc.), flooding also increases the likelihood of human exposure to contaminated water. Figure 4 represents the working model and a basis for testing hypotheses about the role of drainage basin development in facilitating disease emergence. The model has the potential to guide implementation of best practices for watershed or catchment management as a key feature of an integrated disease control strategy. A precise methodology both to quantify and identify pathogenic *Leptospira* in environmental surface waters will provide the data required to test and refine the model (Vinetz et al., 2005).

This research program on the links between ecosystem health and human health using mountain-to-sea microcosms as its study system specifically targets two core sustainability questions. By examining how human transformation of landscapes affects ecological resilience and, in turn, disease risk associated with specific livelihoods (e.g., taro farming), the research exemplifies the problem posed by core sustainability science question 1 in Table 1. Broadening this model to incorporate these anthropogenic changes and the consequences of lost resilience in terms of ecosystem goods and services more generally, will allow it to address core question 4 regarding limits and the development of early warning indicators.

Two essential components allowing each of these projects to succeed so far has been the tenacity of key individuals, and an internal reflection process of community members, as well as researchers and practitioners. Individuals have been willing to take risks associated with going beyond disciplinary boundaries and work outside the reward systems of existing institutions. Also, laying the groundwork for these community partnerships has required many years, a high level of commitment, and putting communities’ needs first. This is especially evident in projects that seek to integrate catchment ecosystem and health (Parkes and Panelli, 2001). Sustaining the success of these initiatives will require not only informal reflection, but also formal evaluation processes focused on measures of capacity building within each project. In this way, evaluation becomes a critical component of building a learning community. It is also a component of the adaptive capacity and resilience that ultimately must be developed and evaluated on a larger scale, contributing to community capacity for health and sustainability in regions, provinces, or states (e.g., Dennis and Liberman, 2004).

Learning from the Past, Looking to the Future

The urgent need for a deeper understanding of the interactions between nature and society, arguably at the core of sustainability, thus, the basis for sustainability science, requires new approaches to research and education that can bridge disciplinary boundaries. Hawai‘i’s unique mountain-to-sea ecosystems, the new paradigms and conceptual frameworks based on the concept of nature and humans as a coupled, complex system, and the cultural renaissance surrounding the traditional *ahupua‘a*, has provided such an opportunity.

The establishment and early progress made so far by this initiative has been possible as a result of several factors. The creation of interdisciplinary research units and federal grant awards providing funding for research infrastructure and centers, as well as training and education funds for fostering, or at least providing the flexibility for, interdisciplinary activities has been essential. While these have been necessary ingredients, they are not sufficient. The coalescing of a tenacious group of researchers, teachers, agency and nongovernmental organization personnel, with equally committed private citizens is the key factor. Moreover, their formation of a “learning community” based on a shared interest in the sustainability of Hawai‘i’s mountain-to-sea ecosystems arguably would not have occurred except for the cultural legacy of the *ahupua‘a* system. As these projects demonstrate, transdisciplinary insights required to advance understanding necessary and to ultimately provide practical interventions have significantly benefited from this approach.

Finally, sustaining this initiative will depend on continuing to break down the institutional and paradigmatic barriers to knowledge exchange outside as well as inside academia. As has often been described regarding the prospects for global sustainability, the present decade represents the turning point. We anticipate that by its close, sustainability science, centered largely on a mountain-to-sea ecosystem perspective in the Hawaiian Islands, yet represented by a far more diverse and perhaps different array of projects described in this “snapshot” will have become an important research and education focus of the University of Hawai‘i.

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