All Hands on Deck: Transdisciplinary Approaches to Emerging Infectious Disease

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Original Contributions

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Abstract: The increasing burden of emerging infectious diseases worldwide confronts us with numerous challenges, including the imperative to design research and responses that are commensurate to understanding the complex social and ecological contexts in which infectious diseases occur. A diverse group of scientists met in Hawaii in March 2005 to discuss the linked social and ecological contexts in which infectious diseases emerge. A subset of the meeting was a group that focused on "transdisciplinary approaches" to integrating knowledge across and beyond academic disciplines in order to improve prevention and control of emerging infections. This article is based on the discussions of that group. Here, we outline the epidemiological legacy that has dominated infectious disease research and control up until now, and introduce the role of new, transdisciplinary and systems-based approaches to emerging infectious diseases. We describe four cases of transboundary health issues and use them to discuss the potential benefits, as well as the inherent difficulties, in understanding the social–ecological contexts in which infectious diseases occur and of using transdisciplinary approaches to deal with them.

Key words: transdisciplinary, social–ecological systems, emerging infectious diseases, HIV, SARS, Nipah virus

Introduction

Over the last 30 years, optimism that infectious diseases will cease to pose large-scale threats to human health has diminished. That optimism relied on ignoring signs of impending trouble such as chemical resistance by microbes

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and their vectors, inadequate antiviral medications, growth of unsanitary megacities, globalized trade and travel of humans and animals, microbially unsafe factory farming and food-processing, and altered human–animal interactions in a rapidly changing landscape. Evidence of the difficulty of controlling infectious diseases through conventional biomedical strategies lies in the long list of human pathogens that have emerged and reemerged in the last three decades: Variant Creutzfeld–Jakob disease, severe acute respiratory syndrome (SARS), Nipah virus, avian influenza, Marburg virus, Lyme disease, HIV/AIDS, malaria, tuberculosis, cholera, plague, dengue, leptospirosis, and West Nile virus, to name a few (Taylor et al., 2001). The fact that these and other diseases have emerged from a wide taxonomic variety of hosts is evidence of the "metaphenomenon" of a global increase in emerging infectious diseases (EIDs).

A symposium entitled "Emerging Infectious Diseases and Social–Ecological Systems" was held in Honolulu, Hawaii in March 2005. The meeting was designed to facilitate interdisciplinary integration as part of the National Institutes of Health Roadmap initiative "Research Teams of the Future" and was hosted by the East West Centre and the Asia-Pacific Institute of Tropical Medicine and Infectious Diseases. The ideas expressed here reflect the experiences and lessons of a group of scholars with expertise in fields ranging from social science to international development, ecology, and various branches of veterinary and human medicine. The article represents the collective ideas of a working group whose task was to focus on the role of "transdisciplinary approaches" as a means to integrate knowledge across and beyond academic disciplines; to enhance our understanding of the social and ecological contexts of infectious disease and, ultimately, to improve prevention and control of emerging infections. The meeting themes of interdisciplinary integration and application of a coupled, human–natural systems approach to emerging infectious disease are elaborated further by Lewis (2005) and Wilcox and Colwell (2005).

While significant successes in controlling infectious diseases, such as antibiotics, vaccines, vector reduction, and water purification, have been achieved through highly specific technological interventions, the rate and scale of global change in agriculture, trade, demographics, species translocations and invasions, microbial adaptation, and other complex factors, have evidently outstripped our ability to understand and respond to EIDs, and exposed serious limitations of approaches that fail to engage with the wider contexts from which infectious diseases emerge. In addition to environmental change, social factors such as income inequalities and governance and social power dynamics add another layer of complexity to the task of understanding and responding to emerging infections. Responding to the EID challenges listed in the first paragraph, therefore, demands attention to the interconnections among social and ecological systems at scales ranging from the village to the globe. Accomplishing this will require new forms of knowledge that integrate the natural and human sciences, attend to dynamics at multiple scales—both spatial and temporal—and engage diverse ways of understanding and intervening.

We chose the title "All Hands on Deck" for this article because the phrase embodies an ethos of cooperation and hard work, and suggests that in order to tackle infectious diseases successfully we must meld ideas from all walks of science, indeed, from all walks of life. The metaphor of a ship is used throughout the article to represent new approaches that, while varying in their specifics, share a common recognition that responding effectively to EIDs will require the integration of a wide variety of disciplinary knowledge, as well as the inclusion of knowledge from outside of academia. To extend the metaphor of a ship, the transdisciplinary approaches examined in this article include critical examination of the nature of the deck, who the deck hands are, and where this ship appears to be headed.

Our goals in this article are:

(i) to outline the disciplinary legacies of the 20th century and the development of systems-based concepts that may inform and frame future approaches to EIDs;
(ii) to describe four examples that (a) demonstrate how the social–ecological contexts of emerging diseases were, or were not, taken into account; and (b) shed light on how transdisciplinary approaches may, or may not, have functioned in these cases;
(iii) to examine the role of transdisciplinary approaches in EID control, including how and when such approaches can arise and/or are warranted; and
(iv) to discuss critical factors that present opportunities and obstacles to designing and implementing more holistic approaches to controlling EIDs.

Historical Context

At the start of the 20th century, western European thought relied primarily on two disciplines to explain and control infectious diseases: microbiology and epidemiology. Early pioneers such as Snow, Koch, and Budd knew that social factors had a strong influence on infections; later researchers like Manson, Ross, and Chagas discovered vector-borne diseases, revealing the importance of transmission ecology. Research from these two periods led to the agent-host-environment model of infectious disease, which still serves as the central model for examining emergence of specific diseases. However, this model fails to shed light on the large-scale social and ecological settings in which the metaphenomenon of increased EID emergence is taking place.

Modern epidemiology's limited ability to thoroughly and systematically address global EID emergence is partly due to the fact that, after drug treatments and disease-vector controls were developed, many epidemiologists shifted their efforts from understanding epidemics of infectious diseases to studying individual risk factors for chronic diseases. Epidemiology's main focus became noncommunicable diseases such as obesity, asthma, vascular disease, cancer, substance abuse, and depression. Epidemiologists in the South were particularly critical of this paradigm, on the grounds that it did not explain large-scale influences affecting groups, and that its ethical and theoretical foundations were flawed (Breilh, 1995). In the North, Krieger called for epidemiological research to engage with the ''web of causation'' (Krieger, 2004). The debates and theories of the 1990s led to the establishment of ecoepidemiology (group level effects), life-course epidemiology (time sequences, socio-biology and intergenerational effects) and social epidemiology (social causation) (Evans et al., 1994; Commentaries, 1998; Ben-Shloma and Kuh, 2002).

While some researchers continued to build understanding of the larger realms in which infectious disease existed, there was a tendency for social and ecological factors to be considered separately rather than interactively. For instance, in Latin America, unequal distribution and access to resources, as well as institutionalized racism, class, and gender inequalities, were given primacy in theories of disease causation, with emphasis on holistic explanatory accounts of infection based on the triangulation of quantitative and qualitative research methods (Laurell, 1989; Almeida-Filho and Goldbaum, 2004), and the transformative potential of ''social ecosystems'' (Breilh, 1991). Elsewhere, scientists studying the ''ecology of infectious disease'' (Real, 1996; Smith et al., 2005) did not necessarily focus on human pathogens but offered biophysical insights with far-reaching implications for epidemiological and biomedical thinking (Wilcox, 2005). As the century ended, calls for integration of social *and* ecological determinants of health penetrated epidemiology and public health, and ranged from socio–ecologic systems perspective (McMichael, 1999), to a proposal for an ''ecosocial'' approach to health (Krieger, 2001). A convergence of systems-based concepts with health and epidemiological research and policy was finally occurring (Parkes et al., 2003, Table 1), with obvious application in research that responds to the linked social and environmental risk factors of emerging infections (Weiss and McMichael, 2004).

Not surprisingly, given that the above developments are recent, hypotheses and research methods that integrate the social and ecological causes and effects of global disease emergence are in their infancy. ''Ecosystem approaches'' to health (Waltner-Toews, 2001; Lebel, 2003; De Plaen and Kilelu, 2004) offer examples of research methods that explicitly engage with the ecological and social systems within which health is created and challenged, although these approaches were not developed specifically for EID investigation. However, these and other systems-based approaches provide some common principles with which to help understand the nested, interdependent systems in which diseases emerge, maintain themselves, and evolve on a multitude of levels—molecular, organismal, communal, national, and global (Wilcox and Colwell, 2005). Understanding of these ''nested hierarchies'' is complemented by the idea of coupled human–natural systems, in which humans are both part of nature and fundamentally conditioned by social activity. This recognition, in turn, encourages researchers to incorporate into their methods and research design the idea that ''delineation between social systems and ecosystems is artificial and arbitrary'' (Berkes et al., 2003, p 2). Research that explicitly engages with the complexity of systems' interactions (Kay et al., 1999), and the associated concepts of adaptation and resilience (Holling, 2001), offer valuable precedents and fertile ground for understanding the social, ecological, and economic contexts in which EIDs occur. Yet, despite these developments, systematic formulation, development, and application of approaches that integrate the social and ecological aspects of disease emergence into research paradigms has not yet occurred. The role of transdisciplinary approaches in helping to achieve such an integration is the central theme of this article.

Anticipating Future Challenges

EIDs in the 21st century confront us with two converging realities: that the causes of social and ecological change (including global poverty and inequity, security, loss of ecosystem services, and others) are also central drivers of EID emergence, and that a piecemeal approach to disease control is often inadequate, and in some cases can exacerbate the original problem. Thus, the potential of combining, integrating, and transcending disciplinary knowledge as a means to enhance responses to complex societal problems and/or to achieve research and educational innovation (Jantsch, 1972; Somerville and Rapport, 2000; Lattuca, 2001; Sapiro, 2004) warrants close examination as an option to improve understanding, prevention and control of future EIDs.

Here, it is useful to distinguish among various types of disciplinarity, as each has uses and applications that cannot be replaced by a single philosophy or approach. McDonnell (2000, p 27) describes multidisciplinary studies as "a collaboration among experts, members of different disciplines, where the relation among them is associative, i.e., where the work of each of them is added to that of all the others." McDonnell proposes that for interdisciplinary studies "the connection is relational, i.e., where the disciplines collaborate in such a way that each takes up some of the assumptions and worldviews and languages of the others," whereas for transdisciplinarity "the integrating language relationship is taken to the extent of there being a transcendent language, a metalanguage, in which the terms of all the participant disciplines are, or can be, expressed." Similarly, Lattuca (2003, p 7) distinguishes synthetic interdisciplinarity, such as arises when teaching issues and research questions "bridge" disciplines, from transdisciplinarity, where research questions "cross" disciplines and the intent is to develop an overarching synthesis where "the theories, concepts, or methods are not borrowed from one discipline and applied to another, but rather transcend disciplines and are therefore applicable in many fields." These distinctions have several implications for devising transdisciplinary approaches to EID control.

First, in keeping with understanding the nested, interdependent nature of social and ecological systems, a transdisciplinary approach defines an EID problem in terms of an open, dynamic system operating at multiple levels (Albrecht et al., 2001, Table 4.1). Albrecht et al. also describe the following as potentially useful elements of transdisciplinary inquiries: the assemblage of a collaborative transdisciplinary team, review of existing knowledge, design and implementation of specific inquiries, data synthesis—with the hoped-for outcomes of creating or enhancing a conceptual synthesis (such as a "common conceptual framework"), and formulating a detailed plan for intervention. Thus, transdisciplinary methodology influences all stages of inquiry—determining research questions as well as design and analysis—even while traditional disciplinary tools, techniques, and methods may examine aspects of the overall synthesis. As such, transdisciplinary approaches can be seen to emerge from systems of knowledge and interrelationships, in the same way that EIDs can be understood as emergent systemic phenomena. Furthermore, the resulting innovations for treatment, prevention, and control of EIDs may be targeted at multiple levels of the social and ecological systems within which diseases arise, which ought to make interventions more successful and longer-lasting.

Second, transcending disciplinary boundaries also requires consideration of different types of integration (Fig. 1) which are introduced and defined here prior to discussing them in our case examples. "Horizontal" integration is defined as integration across knowledge perspectives, such as disciplines or sectors; "vertical" integration means integration among different types of knowledge users, and may include perspectives from academics, as well as local communities and cultures, and NGO staff, for example.

While the two types of integration in Figure 1 function in complementary ways, they are fundamentally different, and should not be conflated. Integration "across" disciplines is one starting point to facilitate a holistic, social–ecological understanding of the metaphenomenon of increased disease emergence globally. However, vertical integration, by lending opportunities to incorporate what Brown et al. (2005) describe as individual, local, specialized, strategic, and holistic knowledge perspectives, provides a variety of new "hands" that can be utilized on deck. Important practical, ethical, and political implications accompany the inclusion of these new "hands" and non-academic voices. This is highlighted by Lebel (2003) in his linking of "transdisciplinarity," "participation," and "equity" through their roles as the three pillars of "ecosystem approaches to human health." Breilh (2003) argues that it is impossible to understand the dynamics and conditions of human infectious diseases without embedding them within the (often inequitable) social relations in which they reside. Approaches to EID control that successfully integrate considerations of participation and equity into their strategies are likely to raise questions about global and local forces driving social and ecological change, and about the needs of those most vulnerable to infectious diseases, in

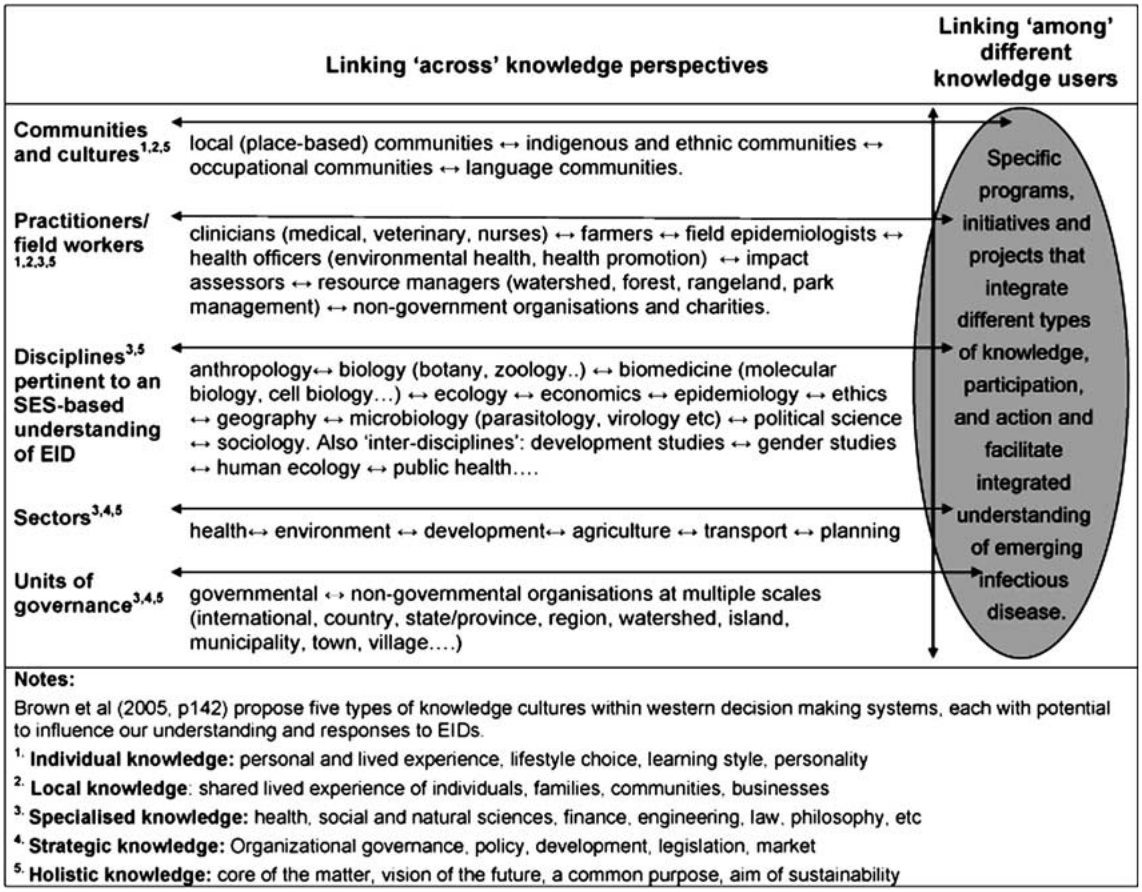

Figure 1. A cross-classification of knowledge by user and perspective.

particular women and children (Gerberding, 2004; McDonald et al., 2004), thereby engaging explicitly with the political economy of health (Krieger, 2001).

Thus, understanding and utilizing horizontal and vertical knowledge integration (while maintaining a less hierarchical and more flexible view of system functioning), is a conceptual juggle we see as challenging but not contradictory. Rather, the capacity to identify and recognize different perspectives on the same issue is a necessary skill for developing a conceptual synthesis that respects the complementary input from a plurality of stakeholders. The following examples and discussion examine the practical implications, opportunities, and limitations of applying transdisciplinary approaches to specific emerging infections.

Case Examples

Here we present four examples, each describing a different transboundary health issue that has implications for understanding infectious diseases. While they are much-abbreviated descriptions of multilayered events, the four examples provide useful reference points for the discussion that follows.

Nipah Virus

The emergence of Nipah virus as a human pathogen highlights the numerous opportunities, as well as some of the obstacles, to linking across disciplines to understand systemic factors influencing EIDs. Nipah virus, first identified in northern Malaysia in 1998 (Chua, 2003), is a highly virulent paramyxovirus, with case fatality rates ranging from 40%–70%; its reservoir hosts are several species of fruit bats (*Pteropus* species). In Malaysia, Nipah virus was transmitted to humans through an intermediate host, pigs. In its initial outbreak over a 35-week period, the virus caused a severe febrile encephalitis in 265 patients, of whom 115 died; 93% of the patients worked in the pig-rearing industry (Lam, 2003). Preceding the outbreak in humans was an outbreak of encephalitis and respiratory disease in pigs (Mohd Nor, 2000). The virus spread to various regions of Malaysia via movement of infected pigs, then briefly to Singapore. Economic losses in Malaysia were estimated at US $500 million (Lam, 2003). Nipah virus' high fatality rate has placed it on the US government's list of potential bio-terrorism agents.

Several theories of Nipah virus' emergence have been posited (Davies and Unam, 1999; Mohd Shahwahid and Othman, 1999; Field et al., 2001; Chua et al., 2002; Motavalli, 2004). Ecological theories of emergence include hypotheses that fire haze from slash-and-burn agriculture negatively affected fruiting trees and led bats to seek out fruit trees planted around pig farms. Though the ecosystem-scale drivers of bat foraging behavior are poorly understood, certainly the proximity of fruit trees and intensive pig farms allowed bats and pigs to come into close contact, which allowed spill-over of the Nipah virus from its reservoir host into domestic pigs, and then to humans.

Viewing Nipah virus emergence through a social–ecological lens, we can generate and examine a range of hypotheses for the cascading factors that led to the unusually close proximity of bats, pigs, and farmers. These factors range from global socio-economic pressures driving the development of intensive agriculture in Malaysia, to regional and local occupational trends leading farm laborers to seek employment on intensive pig farms, and possibly increased contact between bats and humans due to suburban encroachment on bat habitat. Furthermore, feedback loops acting positively (in terms of its relationship with its intermediate pig host) or negatively (in terms of effects on the Malaysian economy) for the virus are reminders that social and ecological systems interact at multiple spatial and temporal scales. The challenges of capturing the complexity of this zoonotic disease outbreak, particularly its social–ecological dynamics, will be explored in the discussion section.

Ertan Dam

The construction of the Ertan Dam offers an example of how health impacts (including infections) can be overlooked, even when social and ecological analyses are undertaken. At 240 meters, Ertan Dam ranks fourth highest in the world, far above the other 22,000 large dams in China, including the Three Gorges Dam. Hydraulically, the Ertan Dam is an extremely important structure in China. By influencing water level 1000 km downstream, the dam has the potential to provide flood protection for 100 million people living in the Yangtze valley.

Ertan was China's first dam built with international bids, and accounts for its largest World Bank loan (nearly $1 billion). Ertan is also China's first attempt to reach an ''international standard'' for managing resettlement of the 46,000 people displaced by its construction, and for mitigating adverse ecological impacts. Two panels of experts—one to manage environmental issues and one to manage resettlement issues—met frequently during the years of dam construction (1991–1999). Anthropologists, engineers, environmental biologists, geographers, resettlement managers, and a responsive dam construction authority worked to minimize disruption to human lives and to the area's fauna and flora. However, the sole international health specialist, who served on both panels, was permitted to focus on only one problem—schistosome infection.

The connection between dam construction and schistosomiasis, a debilitating infection caused by a trematode parasite and hosted by several snail species, is well-documented (Hunter et al., 1993; Jobin, 1999). Ertan's completion was threatened when a live snail of a species known to carry schistosomiasis was discovered in the reservoir area 4 years before it was to be flooded. Three years later, after expensive efforts to survey vulnerable upstream areas, spray molluscicides, engineer snail-resistant water channels, and improve management of human and animal waste, the area was recertified snail-free. No outbreak of schistosomiasis has occurred to date (Gu et al., 2001), but other infections (such as HIV and other infectious diseases resulting from high-risk behaviors and vulnerability of populations affected by the dams), and general health effects (endemic diseases of poverty, despair, inadequate water supplies, poor sanitation, and malnutrition) remain undocumented and unaddressed (Sleigh and Jackson, 2001). The Ertan case exemplifies the limitations of studying through a single lens complex issues that, by their nature, transcend single disciplines, sectors, and/or diseases. The case provides an excellent opportunity to consider how a more holistic, more integrated health assessment could have been conducted—one that would have recognized the social and ecological impacts of dams as drivers of EIDs and related determinants of health.

SARS

Our capacity to overcome disciplinary and sectoral boundaries in response to crises is demonstrated by the collaborative approach that was used to control SARS in British Columbia, Canada. On March 12, 2003, the World Health Organization announced a global outbreak of an atypical pneumonia (WHO, 2003). The origin of the novel coronavirus causing SARS was traced to Guangdong Province, China, but SARS spread quickly to Hong Kong, then internationally. Health care resources in affected areas were severely strained by the outbreak, and it became apparent that, in many jurisdictions, basic infection control and occupational health principles were neither clearly understood nor consistently applied.

Unlike in Canada's other affected city, Toronto (Varia et al., 2003), when SARS appeared in Vancouver, BC there was only one case of secondary transmission, to a nurse who had been occupationally exposed. While the successful control of SARS in BC was clearly multifactorial, an important element was the prompt adoption of a multistakeholder approach. An interdisciplinary team from the University of British Columbia, Occupational Health and Safety Agency for Healthcare in BC, and BC Centre for Disease Control, as well as governmental health authorities and representatives from health care workers' unions and the Workers' Compensation Board, quickly developed a unified approach (Yassi et al., 2003) and guidelines to limit the spread of infection (Provincial SARS Science Committee [PSSC], 2003).

The group compiled a report (Yassi et al., 2004) that addressed questions such as "What level of protection (types of eyewear, respirators, face shields, etcetera) is necessary to ensure the safety of health care workers?" and identified other important knowledge gaps. To generate this report, researchers, including experts in occupational medicine and hygiene, infection control, public health, epidemiology, and respiratory therapy, as well as researchers studying respiratory particle transmission and clinical staff, reviewed the literature and a series of focus groups were formed. Afterward, recommendations for key areas requiring further study were developed by consensus (Gamage et al., 2005; Moore et al., 2005; Yassi et al., 2005), which served as a tool to direct future research, and to develop evidence-based practice in the interim. By September 2004, 23 train-the-trainer sessions to engage and educate front-line workers had been completed across BC. In short, the benefits were clear to taking a proactive and integrated approach to emerging disease control.

Early Warning Rapid Response System: A Systems-based Transdisciplinary Approach to Building HIV Resilience

The importance of working across boundaries is demonstrated by the innovative approach to HIV/AIDS taken by the Association of South East Asian Nations (ASEAN) and China (Hsu et al., 2000, 2004). The Early Warning Rapid Response System (EWRRS) relies upon simultaneously addressing international, regional, and local dimensions of HIV transmission, and has been a key development arising from the socio-economic cooperation among the 10 ASEAN member countries (Brunei, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Viet Nam) and China, a member of the Greater Mekong River Group. All of these countries have rapidly growing populations and are linked by the ASEAN Highway Network.

When SARS emerged, the ASEAN countries jointly mobilized immigration officials, border security personnel, and air and land transportation sectors to work with health authorities to contain the infection. In contrast, the more lethal and insidious impacts of HIV/AIDS have required developing and implementing a social–ecological approach to build resilience to HIV in South East Asia (Hsu et al., 2003). Although developed for HIV, the EWRRS framework (Fig. 2) is applicable to many other infectious diseases.

The large population movements that accompany infrastructure construction, as well as improved transportation networks that open up opportunities for trade, commerce, travel, and an expanded sex industry, provide opportunities to spread HIV. Thus, to preserve the economic and social opportunities presented by construction while preventing further spread of HIV, the ASEAN countries agreed to coordinate efforts of finance and planning, construction and transportation, agriculture and rural development, and health planning in the form of an international AIDS committee. The committee's goal was to maximize the utility of investments provided through infrastructure construction, while mitigating the potential negative impacts such construction might bring to surrounding communities.

Early successes of the EWRRS' activities resulted in commitments by the participating governments to extend implementation of the EWRRS from its initial 2 years to a 5-year commitment lasting until 2009. The EWRRS provides an example of a specific initiative that facilitates horizontal coordination across sectoral, agency, national, and disciplinary boundaries, as well as fostering vertical collaboration between central and local governments, international donors and organizations, research teams, NGOs, and local communities (as per Fig. 1).

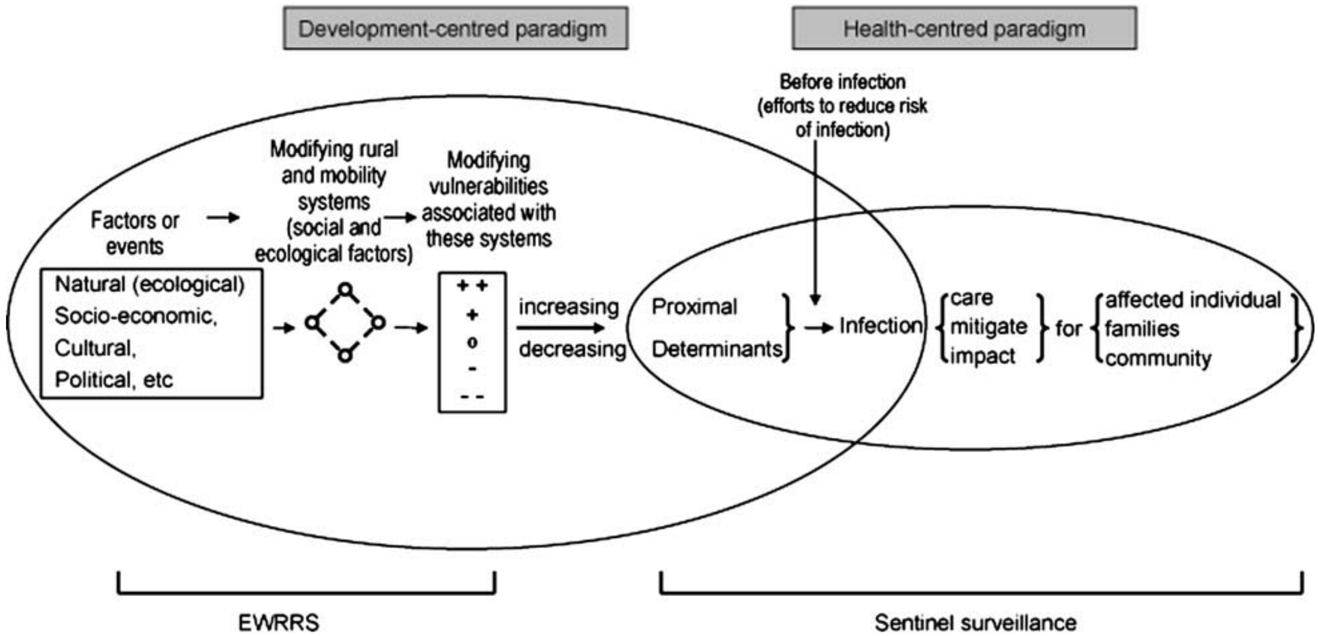

Figure 2. Integrating health- and development-centered paradigms to respond to infectious disease: the early warning rapid response system (EWRRS) concept. Symbols: "o" = no influence on vulnerability or health impact; "+" = increase in vulnerability and/or health impact; "–" = reduction in vulnerability and/or health impact. These influences may vary over space and time with implications for both health and development paradigms. A flood may increase vulnerability by disrupting crop cultivation or harvest resulting in loss of income in the short term, but in the long term may replenish the fertile alluvial soil and reduce dependence on external fertilizers. Likewise, in the short term, an irrigation canal may enable dry-season cultivation and enhanced income generation. This may reduce vulnerability through poverty reduction, but also provide new habitats for disease vectors and/or salinization of soils not suitable for dry-season irrigation, thus decreasing crop-yields, and increasing poverty and vulnerability in the long term. Adapted from Hsu et al. (2004), with permission.

Lessons Learned

As is apparent from the above examples, artificial distinctions between social and ecological systems limit our understanding of the larger contexts of global EIDs. The multifactorial nature of disease emergence clearly demands inclusion of expertise across scientific disciplines and across varying knowledge sources, from indigenous to academic. In this sense, added perspectives and sources of knowledge (or "all hands on deck") can increase the likelihood of improving long-term control of infectious disease emergence.

Linking across Disciplines

A range of analyses of various disease emergences through a social–ecological lens, from *E. coli* (Ali, 2004), to leptospirosis (Barcellos and Sabroza, 2001), schistosomiasis (Clennon et al., 2004) and cholera (Follér, 2001; Collins, 2004), already exists. Key themes emerging from such analyses are that nonlinear processes frequently operate across variable scales (Turner et al., 2003; Foley et al., 2005; Wilcox and Colwell, 2005), that improved surveillance and intervention are necessary across the socio-behavioral and ecological spectra, and that new hypotheses about disease emergences can be generated when researchers are not limited by disciplinary constraints in research design and implementation.

While the Nipah investigation accomplished the step of using an interdisciplinary team of medical, ecological, and molecular and genetic researchers (Field et al., 2001), the "next step" of explicitly incorporating social science perspectives into the investigation was, to our knowledge, not achieved. Whether or not the hypothesis that fire haze contributed to the Nipah outbreak is ultimately substantiated, there is a clear need for better understanding of the significant role that economic and cultural factors (such as the design and construction of intensive pig farms in areas that contain fruit bats) played in Nipah's emergence. The fact that, to date, little research that spans these social and ecological concerns has been conducted may reflect the significant challenges of conducting interdisciplinary research that bridges social and biophysical disciplines. Competing jargon and perceived incompatibilities often arise when different academic cultures meet (McDonell, 2000), and need to be clearly addressed for interdisciplinary investigations of EIDs to succeed. Precedents show these hurdles can be overcome with patience, respect, and prioritization of problem-solving over territory-defending (Salter and Hearn, 1996).

Even when such comprehensive horizontal integration *is* achieved, it can remain ''academic integration'' only, if the research is disconnected from place-based understandings of policy actors and affected communities. Participatory social research methods can provide an explicit mandate to link ''vertically'' among academic, local, and policy knowledge (Parkes and Panelli, 2001). Such approaches have been used to integrate multiple perspectives and to guide interventions to control infectious diseases such as cholera among the Shipibo-Conibo people in Peru (Follér, 2001), and in cystic echinococcosis control in Nepal (Waltner-Toews et al., 2005).

Toward Transdisciplinary Integration

It is possible to gain understanding about when and where transdisciplinary approaches can arise, regardless of whether explicit connections to the social and ecological contexts of an emerging infection are made. Acute public health emergencies (including of emerging diseases) seem able, at least in the short term, to overcome disciplinary, sectoral, and cultural boundaries. After the tsunami of December 2004, which killed at least 174,000 (MMWR, 2005) and left over a million people homeless, there was an outpouring of money, expertise, goods, and more. Yet, the deaths from HIV—20 million people between 1981–2003—(UNAIDS, 2004) and diarrhea—estimated at 2–2.5 million mortalities a year—(O'Ryan et al., 2005) do not elicit the same reaction. Similarly, while experts from different fields fight to control less acute (albeit more pervasive) public health catastrophes, a new and rapidly spreading threat such as SARS somehow creates unity. Such team-building is often characterized by both horizontal and vertical integration, and by a pragmatic willingness to collaborate when confronted with sudden and unexpected threats.

Experts in risk perception have long recognized that public acceptability of risk from immediate threats is much lower than that of risks posed by longer-term threats. In the urgency of the situation, we put our differences aside and get on with the task. Why do we not do the same for threats of equal or greater magnitude that have a slower speed of onset? In part, because doing so would require changes at the level of large institutions, including scientific and academic ones, and thus may be threatening to current institutional and power arrangements in ways that emergency responses are not.

While we cannot fully explain this dichotomy of responses, valuable lessons can still be extracted from them. For example, it may be possible to harness the good will and teamwork established during an emergency in order to address health issues that develop more slowly, such as the spread of tuberculosis, of malaria's range, or the unfolding threat of avian influenza. As such, the cooperative groundwork and collaboration-building of a crisis may be the ''silver lining'' of the emergency cloud.

However, while transdisciplinary integration may serve well in a crisis, it does not necessarily address the systemic social and ecological drivers of EIDs. In the case of SARS, the investigation and solutions that were forged during its emergence were certainly effective in controlling disease spread, particularly in British Columbia. However, to achieve long-term control and understanding of SARS, explicit analyses of social and ecological drivers of disease (such as in-depth investigations into the health and socioeconomic status of workers in game markets), or large-scale analyses of ecological drivers of diseases particular to southern China (such as the mixing of farmed game animals with poached wildlife species) must be introduced into the picture. Some attention to these less-obvious drivers of disease was paid, but, as far as we are aware, was sporadic, even among studies that were put into place long after the immediate crisis had passed.

All Hands on Deck?

Our examples of the Ertan Dam and building HIV resilience provide examples of the difficulties, and of the great potential, of developing approaches to EID control that recognize that health and development are inextricably intertwined. In the case of the Ertan Dam construction, the narrow focus on schistosomiasis, rather than on examining the interrelated facets of the ''health/dam'' connection (Sleigh and Jackson, 2001), poses numerous questions about how a more integrated health assessment might be conducted. Existing reports on health effects of dams have tended to focus on a specific vector-borne disease (Amerasinghe, 2003), or have subsumed ''health impacts'' within social effects (WCD, 2000). Yet, the rate and scale of change created by large dam projects demand integrated multiyear assessments of health impacts (Banken, 1999), in which emerging infections are seen as one of multiple "downstream" effects of widespread change to social and ecological systems (Parkes et al., 2003), and human health is recognized as the ultimate criterion for sustainability (McMichael, 2002).

The HIV example presents us with an example of sustained horizontal and vertical integration, and of successful conceptual synthesis. In the EWWRS, both the disciplinary *and* sectoral scope of HIV are considered through interrelated factors such as immigration, international relations, air and land transportation, trade and commerce, and prostitution. Drivers of social and ecological change are seen as equally relevant to both development and health paradigms (Fig. 2), and point to the nested (international, national, local, and individual) interrelationships that need to be considered in order for an HIV early-warning system to be effective.

The HIV early-warning system also provides an example of the practical challenges of an approach that traverses cultural, governmental, and economic boundaries, and also demands attention to the equity issues embedded within ecological and social changes. The implementation of "farmer-life schools" as a component of this project was a particularly interesting approach, and was done with the goal of empowering communities affected by HIV with specific tools to deal with inequity (du Guerny et al., 2002; Sokunthea, 2002). For example, through the teaching of integrated pest-control (including agro–ecosystem analysis for healthy rice crops), participants in the life-schools were guided through a personal "human–ecosystem analysis," in order to identify and address the links between their HIV risk-factors (traveling away for work, gambling, use of prostitutes) and associated factors of landlessness, food security, poverty, loss of farm productivity, and lack of education. Here, addressing embedded social–ecological inequities is seen as integral to the process of understanding an infectious disease, provoking researchers and participants alike to engage with, confront, and respond to these interrelated concerns.

Conclusions

Three key themes illustrate some of the obstacles to, and opportunities for, improving infectious disease prevention via transdisciplinary innovation.

Medical Technology Alone Cannot Solve the Problem of EIDS

Disciplines such as molecular biology and immunology have given rise to medical therapies and tools such as vaccines and drugs to control disease vectors that seem, on their surface, to promise more global solutions with fewer requirements to consider the political and social dimensions of the work being done. However, the idea that such narrowly defined, but scientifically sophisticated, medical interventions can respond to the global challenge of disease emergence is receiving criticism (Birn, 2005). This is, in part, because recent and ongoing outbreaks of avian flu, SARS, Marburg virus, Ebola, and numerous other diseases (Lashley, 2004), have drawn public and scientific attention to the fact that problems of emerging diseases are not easily solved by "magic bullet" interventions. Stirring political debates about access to costly AIDS medications, participation in polio eradication programs, and the ethics of clinical trials in Africa and Asia that test medications that may not be available to participants post-trial, have also drawn broad sectors of society into discussions of the political aspects of health and disease.

Arguably, attention to the social–ecological and political contexts of global health is now at an all-time high, making the time ripe for precisely the kinds of new approaches to emerging disease research for which this article calls. Yet, just as single-discipline researchers need to maintain a healthy critique of their contributions, so too must those who seek to develop and utilize transdisciplinary approaches engage their abilities to analyze and criticize their contributions. Though integrated conceptual frameworks and disease control measures founded on complex understandings of social and ecological systems may be informative and grounded, they may not always be feasible or universally desired. A large portion of the mainstream biomedical community is biased against complex social, political, and environmental research on the grounds that such research often depends on more variable, hard-to-measure factors. Those dealing with EID threats will need to remain aware that, while multilayered approaches may produce results that more accurately reflect the uncertainty of real life, such approaches may be challenged on the basis that they often do not lend themselves to straightforward, rapidly-implemented policies or interventions (Ravetz, 2005).

Clear Communication Is Required to Cross Disciplinary Boundaries and Demonstrate Success

Another difficulty in achieving productive transdisciplinary work is the differences in discourse and dialects among disciplines; overcoming these difference will require a period of translation and mutual learning. Training in teambuilding and facilitating team dynamics, as well as in basic skills such as active listening, can help reduce the time it takes to develop productive collaborations in interdisciplinary research efforts, thus dissipating some of the inevitable frustrations. Such collaboration will be further aided by clear communication of the benefits of crossing disciplinary boundaries.

If transdisciplinary approaches yield longer-lasting effects, make medical interventions more successful or less necessary, provide health-care access to more sectors of the community, and more effectively address economic and gender inequities than do standard biomedical interventions alone, these gains can help achieve a fundamental shift in devising and implementing disease-prevention strategies. The successes, and policy relevance, of these approaches will be key to their institutionalization (Lebel, 2004). Additionally, teams and communities of transdisciplinary researchers must communicate their successes and failures so that they are understood by a wide range of audiences and measured by appropriate indices, particularly because holistic systems-based research can take a long time to complete and tends not to make the same splash as large drug or vaccine trials. Substantial outreach and education efforts will be required to achieve these goals, which include communication with, and participation by, those whose health is being studied as well as by decision-makers at multiple levels, from emergency physicians and veterinarians to funding agencies and global policy makers.

Two recent analyses of decade-long, ecohealth-based research projects, one in a Brazilian Amazon fishing village (Mertens et al., 2005) and the other in Kathmandu, Nepal (Waltner-Toews et al., 2005), are instructive. Although each was initiated based on a "simple" problem (mercury poisoning in Brazil, cystic echinococcosis in Nepal), both led to profound and positive social–ecological transformations of communities through a combination of local engagement and ongoing research. Other examples of successful approaches to disease management are coming to light, whether in "acute" cases such as the SARS outbreak, or for long-term disease control, such as of onchocerciasis in West Africa, and Chagas' disease in Brazil (Hotez et al., 2004). The past few years have seen wide acceptance by the infectious disease and public health communities that changing land-use patterns (e.g., deforestation, urban and suburban encroachment on wildlands), along with migration and air travel, are playing a major role in infectious disease transmission (Hotez et al., 2004; Patz et al., 2004; IOM, 2005). This recognition could pave the way for the current practice of studying one outbreak at a time to be replaced by more powerful approaches that seek to understand and explain the metaphenomenon of emergence from multiple hosts in multiple settings.

Researchers Have an Essential Leadership Role

Research on the complex interconnections of infectious disease emergence demands innovative ideas and scholarship that can combine social scientific, ecological, and population health research to build new methods that bridge stakeholder interests. Transdisciplinary research demands a radical shift in the funding strategies of many national and international agencies, whose missions often preclude allocating the necessary resources to address interlinkages across strictly defined—and sometimes overly specialized—problems. In academia, current tenure and reward systems generally do not promote the interdepartmental collaboration in research and training that is required to advance discovery in this field.

While single-discipline projects still dominate infectious disease research, this paradigm is changing due to increased perception by funding agencies that multi-, inter-, and transdisciplinary research will lead to bigger breakthroughs (Colwell, 1998; Zerhouni, 2003). Scientific and technical innovations in low-cost diagnostics, GIS, multivariate statistical analysis, mathematical modeling, and database management are creating opportunities to integrate previously disparate types of data. The emerging "One Health" perspective—linking human, wildlife, and ecosystem health—provides a platform for collaborative approaches to infectious disease research, particularly in the case of zoonoses (Daszak et al., 2000; Aguirre et al., 2002; Wilcox and Aguirre, 2004).

Another important research development is the adoption of methods that depend on community or multistakeholder participation in order to better address issues that span environmental health and sustainability concerns (Merrifield, 1993; O'Fallon and Dearry, 2002; Witten et al., 2000; Parkes and Panelli, 2001; Bunch, 2003; Waltner-Toews, 2003; Brown et al., 2005). Infectious disease researchers are beginning to follow this lead, in-formed not only by the positive impact of participatory research on communities, but also by the increased attention to the rights of underrepresented and indigenous communities around the world that is changing the political landscape of donor participation in development, the environment (Chapin, 2004), and health (GFHR, 2004). Innovative research projects that bridge disciplines and engage with place-based knowledge sets of communities vulnerable to EID infection, as well as with non-academic stakeholders who work with such communities, have great potential not only to increase our capacity to prevent and control emerging infections, but also to meet maturing demands of 21st century funders and donors.

An important indicator that leadership, and the drive to spearhead new approaches, are growing within the research community is the fact that attention is shifting from asking *why* it is necessary to build collaborative networks across different types of knowledge, to figuring out *how* this work can be initiated, maintained, and evaluated (Funtowicz, 1994; Gross Stein, 2001; Klein et al., 2001; Horlick-Jones, 2004). It is no longer enough for scientists to hone their own corners of research to perfection, and assume someone else (who?) will put it all together. Increased sophistication in efforts to incorporate systems-based concepts regarding ecology, health, and sustainability into professional curricula (Howard, 2004; Howard and Rapport, 2004) is a step in the right direction for a new generation of researchers. We must also find ways to cultivate leadership in the current generation of researchers because it is they who will be required to build the collegial and collaborative platforms from which to bridge disciplines and policy, and make useful contributions in the multistakeholder arena of EID investigation and control. Critical skills will be required to identify how, when, and where disciplinary, interdisciplinary, and transdisciplinary approaches will be required in building responses to disease emergence. This is not a small task or an ''academic exercise,'' but a necessary step in building our capacity to better respond to the emerging infections of the 21st century.

In the short term, transdisciplinary approaches may not always work as well as narrowly focused methods to improve efficiency of production systems, or to generate drugs and vaccines. However, if we accept that emerging diseases are symptoms of systemic dysfunctions and manifestations of our failure to live sustainably, and if we wish to prevent the occurrence of future epidemics, then reconstructing our views of infection along these lines is our best and brightest hope. As epidemiologist and health historian A.J. McMichael has said, ''trandisciplinarity is more than the mixing and interbreeding of disciplines. Transdisciplinarity transports us: we then ask different questions, we see further, and we perceive the complex world and its problems with new insights.''(McMichael, 2000, p 220). When we are able, by inviting as many hands on deck as we need, to utilize the collective intelligence of society, we will have built a ship that can stay afloat on the rough seas that surely lie ahead of us when it comes to tackling global disease emergence. The laboratory for sustainability is us, and there are no replicates.

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