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CONSERVATION BIOLOGY AND THE HEALTH SCIENCES

Defining the Research Priorities of Conservation Medicine

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Human impacts on the health of the planet can be characterized within four areas of environmental concern (Colborn et al. 1993; Colborn et al. 1996; Rees 1996; Wilson 1988; Woodwell and Houghton 1990):

1. increasing biological impoverishment, which includes the loss of biodiversity and modification of ecological processes;
2. increasing global "toxification," which includes the spread of hazardous wastes and toxic substances and the impact of endocrine-disrupting hormones;
3. global climate change and ozone depletion; and
4. an increasing human "ecological footprint" as a result of our exponentially growing population and use of resources (an ecological footprint is an area-based calculation used in environmental economics to determine human impacts on natural resources).

The discreet and cumulative impacts of these human-induced global changes not only have diminished the environmental capital of the planet but also have yielded an array of health concerns, including the increasing spread of infectious (e.g., malaria) and noninfectious (e.g., melanoma) diseases, and the growing physiological impacts on species' reproductive health, developmental biology, and immune system response (e.g., endocrine disruptors) (Blaustein et al. 1994; Blaustein and Wake 1995; Colborn et al. 1996; Laurance et al. 1996; Epstein 1995; McMichael and Haines 1997; Patz et al. 1996).

The ecological impacts of humans can ripple throughout ecological communities. The demise of one species, or the rise of one species at the expense of another, may establish a trophic cascade of ecological responses (see chapter 3). When predator-prey or species competition relationships are disrupted, ecological impacts may extend beyond the predator and prey or the competitors (Estes et al. 1998; Epstein et al. 1997; Pace et al. 1999; Ostfeld and Keesing 2000b). The spread of Lyme disease as a result of the changing ecology of white-tailed deer (*Odocoileus virginianus*) and white-footed mice (*Peromyscus leucopus*) in a landscape devoid of large predators and diminished biodiversity is a good example of ecological magnification of disease (Ostfeld and Keesing 2000a).

Certainly global climate change adds to the complexity of disease impacts in conservation. This issue is one of the most pressing ecological health concerns. For instance, global climate change may impact health by promoting the spread of infectious disease from more tropical ranges to temperate areas, expanding beyond latitudinal and altitudinal zones. This phenomenon may be apparent in diseases such as malaria and dengue fever (Epstein 1995, 1997; Patz et al. 1996; Rogers and Randolph 2000). The potential impact of climate change on ecological processes may be profound: increased precipitation in some regions and drought in others; increased erosion of the coastal zone with rising sea levels; and the inability of many species to adapt to the relatively rapid changes in climatic regimes, potentially resulting in mass extinctions (Epstein 1999; McMichael 1997; McMichael at al. 1999). Changes in atmospheric volatilization and deposition of pollutants also are of concern as warmer temperatures and greater precipitation enhance pollutant transport (Blais et al.1998; Schindler 1999).

Since its origin, conservation biology has understood the implications of health and disease in management of species and habitat. The integration of theory into practice is only recently emerging with the rise of the new field of conservation medicine (Frankel and Soulé 1981; Dobson and May 1986; Grenfell and Dobson 1995; Meffe 1999; Pokras et al. 1999). Understanding the ecological aspects of health and disease is a future challenge for conservation biologists, who are increasingly expected to provide management remedies for ecological health concerns.

Conservation Medicine: A Brief Description

Conservation biology and conservation medicine have the common aim of trying to achieve ecological health. Conservation medicine studies the two-way interactions between pathogens and disease on the one hand, and species and ecosystems on the other. It focuses on the study of the ecological context of health and the remediation of ecological health problems. In response to the growing health implications of environmental degradation, conservation medicine has emerged as a new interdisciplinary field to address the complex interrelationship between health and ecological concerns. As such, conservation medicine's purview includes examining the linkages among (1) changes in habitat structure and land use; (2) emergence and reemergence of infectious agents, parasites, and environmental contaminants; and (3) maintenance of biodiversity and ecosystem functions as they sustain the health of plant and animal communities including humans. For example, conservation medicine is concerned with the effects of disease on rare or endangered species and on the functioning of ecosystems. It is also concerned with the impacts of changes in species diversity or rarity on disease maintenance and transmission.

The dynamic balance that we term health is conceptualized using a set of widely varying spatial scales by many disciplines including human medicine, public health, epidemiology, veterinary medicine, toxicology, ecology, and conservation biology. Conservation medicine represents an approach that bridges those disciplines to examine the health of individuals, groups of individuals, and the landscapes in which they live as an indivisible continuum (Meffe 1999; Pokras et al. 1999).

Conservation medicine, like other interdisciplinary approaches, brings together scientific disciplines "long separated by academic and practical tradition" (Wilson 1992). By reaching out to multiple disciplines, conservation medicine provides new skills, tools, and vision to the fields of both conservation biology and medicine. This includes bringing biomedical research and diagnostic resources to address conservation problems such as development of new noninvasive health monitoring techniques; training health professionals and conservation biologists in the promotion and practice of ecological health; and establishing interdisciplinary teams of health and ecological professionals to assess and redress ecological health problems.

Why Should Conservation Biologists Care about Disease?

Pathogens and infectious diseases create special problems for both the protection of endangered species and the maintenance of biodiversity. In several cases the introduction of a pathogen has produced a significant further decline in the numbers of an already endangered species: canine distemper in black-footed ferrets (*Mustela nigripes*) (Thorne and Williams 1988; Williams et al. 1988); rabies and canine distemper in hunting dogs (*Lycaon pictus*) in Serengeti (Dye 1996; Ginsberg et al. 1995; Heinsohn 1992); and avian malaria in endemic Hawaiian birds (Warner 1968; van Riper III et al. 1986). In all of these examples, the pathogens involved utilized common or domestic species as reservoir hosts. There is increasing evidence that species diversity may provide an important buffer that minimizes the impact of a pathogen on a population. Paradoxically, pathogens may also play a role in both maintaining biodiversity and driving processes that lead to increases in local diversity (Augspurger 1984; Gilbert 1995; Gilbert et al. 1995; Van der Putten and Van der Stoel 1998; Van der Putten et al. 1993).

While increased species diversity may affect the ability of a pathogen to "find" a susceptible host (especially if the pathogen utilizes multiple hosts), many pathogens are so species specific that only the density of a population affects their ability to cause disease. And thus, any sudden change in population demographics and proportion of susceptible hosts within a population can alter pathogen distribution (Aguirre, Hansen, et al. 1995). This density-dependent phenomenon can be demonstrated in various management practices, such as translocations; reintroductions; the creation of feeding stations in winter that bring animals into close contact, such as the National Elk Refuge in Wyoming; and the alteration of traditional migratory corridors that may bring wildlife into closer contact with domestic animals—all of which can facilitate disease spread (Aguirre, Starkey, et al. 1995). Many activities used to manage wildlife populations have the potential to alter pathogen transmission patterns, and conservation biologists need to be mindful of the consequences. To understand disease threats to wildlife populations, some level of basic disease ecology is required. Conservation biologists need to know what pathogens are endemic and use that information to assess and remedy the introduction of exotic pathogens into a population (Aguirre and Starkey, 1994).

Three topics are central to our understanding of the role pathogens play in conservation biology:

1. What roles do relative abundance, susceptibility, and overlap in spatial distribution play in determining rates of pathogen transmission in populations of vulnerable or endangered species? In pathogens that utilize a range of host species, how do these features contribute to cross-species (inter-specific) transmission? More precisely, does ecological information on the behavior and spatial distribution of potential host species complement epidemiological data and allow us to identify species that are most likely to act as reservoir hosts for pathogens that provide a significant threat to rare or endangered species?
2. What are the dynamics of a recently introduced pathogen into a population? In particular, how do deterministic and stochastic factors interact to determine the persistence and extinction of pathogens in populations? Significantly, how are the dynamics affected if the population is small? How do different types of pathogens contribute to further declines in the abundance of potentially endangered host species?
3. Does the local diversity of species used by a pathogen tend to buffer or increase either its persistence or rate of spread? Can a pathogen alter the diversity of species that coexist in any community?

Central to all of these problems is the development of a quantitative understanding of how pathogens affect the dynamics of communities that contain one or more potential host species. Here we need to develop empirical and theoretical analyses that examine the role that pathogens play in mediating the coexistence of potentially competing species or in maintaining genetic diversity within a single host species. *We then need to examine whether the diversity of host species tends to either buffer or amplify disease outbreaks.* This is probably the central question in understanding the role that pathogens play in conservation biology. It has very practical applications in conservation, because many proposed management strategies are based on the rationale that biological diversity leads to greater resilience (Pimm 1984; Schulze and Mooney 1994; Hollings et al. 1995).

Determining the answers will require the exploration of the ecological interactions between mode of transmission, host diversity, and pathogen persistence. This can be performed only by examination of empirical data for a number of systems in which we can dissect the relative roles played by host abundance, host resource utilization, and host spatial distribution in determining rates of intra- and interspecific transmission.

In conjunction with these largely deterministic and analytical exercises, we also need to understand the population dynamics of epidemic outbreaks in small (endangered) populations. These analyses will eventually allow the development of stochastic models that determine the impact of pathogens on populations that are too small to sustain a long-term persistent source of infection. Here we also need to focus on examining the costs and benefits of intervention to prevent further spread of the disease, particularly in the limiting case where small host population size always leads to the eventual extinction of the pathogen.

Understanding the Ecology of Disease: An Essential Guide for Conservation Biologists

Pathogens, also known as infectious agents, include viruses, bacteria, fungi, protozoans, and helminths. They undergo population fluctuations within hosts; they compete with one another for access to resources, such as cells and nutrients within hosts; they are preyed upon by host immune agents; they select habitats (tissues); and they disperse within and among hosts. For those pathogens that are zoonotic (i.e., those that reside within nonhuman vertebrate animals and are transmitted to humans), and those that are transmitted by vectors, ecological interactions are even more complex. Such pathogens must contend with differing environmental conditions within human hosts, nonhuman hosts, and vectors. In addition, the vertebrate hosts and arthropod vectors are involved in complex ecological interactions of their own that will influence the maintenance and transmission of pathogens.

An example of an emerging infectious disease with strong implications for conservation medicine is the 1999–2000 "outbreak" of West Nile virus (WNV) in the northeastern United States (Lanciotti et al. 1999). This mosquito-borne disease, endemic to Europe, Africa, and the Middle East, appeared suddenly in birds and humans in and near New York City and elicited a response by public officials that included extensive aerial spraying of insecticides in densely populated areas. This remedial action, which may be more dangerous to public health and wildlife than the disease itself, *and* ineffective in reducing disease incidence, was implemented despite our ignorance about the ecology of the mosquito vectors, bird reservoirs, and the pathogen.

For a disease such as this, that has achieved almost daily attention from the mass media, our level of ignorance of the risk and its ecological causes is astonishing. Questions to which no thorough answer exists include: How did WNV disperse to the Western Hemisphere, or was it here all along? Which species function as reservoir hosts (i.e., those from which the mosquito vectors obtain the pathogen)? In which species is the virus pathogenic or lethal, and how does infection influence population dynamics of those species? Over what area does WNV occur, and how does it get there? How do patterns of temperature and rainfall influence breeding performance and populations of container-breeding mosquitoes in urban and suburban ecosystems? Can WNV exist in mosquitoes other than *Culex pipiens* and *Aedes japonicus*? How does the pathogen overwinter? Does it migrate south or stay dormant during the cold winter months (Aguirre et al. 1992)?

Several general principles relevant to conservation medicine are represented by the WNV example. First, in the absence of information on the ecological determinants of disease risk, as well as on the magnitude of that risk, environmentally destructive but largely ineffective measures (e.g., adulticide spraying) are unfortunately employed. Ecological knowledge about zoonoses can help prevent uninformed decision making. Second, environmentally more benign solutions to the WNV problem may require a solid scientific understanding of the roles played by specific bird or mammal reservoirs, diversity in the community of reservoirs, and landscapes that influence diversity. Third, a likely cause of the transoceanic dispersal of the virus is either via movements by people or by domesticated or wild animals (Rappole et al. 2000). Long-distance movements by pathogens such as WNV may represent instances of invasion by exotic species and, therefore, are relevant to both conservation biologists and health scientists. Fourth, some evidence suggests that the container-breeding mosquitoes that carry arthropod-borne viruses become particularly abundant when hot, dry weather prevents flushing of urban pools of water, such as storm drains. Climatic factors may influence disease transmission in unexpected ways (Reisen et al. 1992; Hubalek and Halouzka 1999).

Ecological research can help us anticipate and ameliorate the adverse effects of infectious diseases on humans, domestic animals, and wildlife. From an ecological framework, these infectious diseases occur when a pathogen population disperses to a host, invades, and, via infection, triggers a host immune response resulting in clinical signs. The key elements to which ecological research can contribute is an understanding of where pathogens are maintained in nature, how they disperse to the focal population, and what environmental processes are involved in the maintenance of the pathogen within populations and in transmission among them. Armed with such knowledge, conservation managers may be able to intervene in natural systems to reduce the likelihood of exposure. In box 8.1, we have listed potential research priorities, posed as questions, together with a brief rationale, that link disease, ecology, and conservation biology.

Connecting Pathobiology to Ecology

Investigation of disease and disease pathogenesis is based primarily on studies in domestic animals. However, it may not be accurate to assume that principles developed by studies in domesticated animals will apply to wildlife. Even within the same species, extrapolation across animals from a range of different habitats may be problematic. This is because many infectious agents endemic to a population are adapted to the population structure of their hosts. Dynamics and structure of a host population determine the nature of its microbiologic fauna. Isolated or small populations may maintain different types of pathogens than large and contiguous populations that freely exchange individuals. Because both the genetics of the pathogen and the host environment determine the outcome of infection, it is plausible that in isolated populations, genetic bottlenecking of both host and pathogen may lead to a unique outcome of infection. Thus, although detailed pathogen-host studies provide suitable information, and frequently the only baseline information available, the potential for unique pathogenic outcomes in wildlife species should be considered.

A primary objective should be to determine the extent to which disease caused by endemic microbes can influence survival or fecundity of individuals in a population. Endemic diseases are infrequently considered as factors affecting population survival. Yet infections with endemic organisms may more commonly lead to chronic conditions affecting an animal's ability to forage or escape predators than directly to high mortality. In addition, disease induced by infectious organisms common to a population may have a more profound effect on specific age-classes such as neonates or old adults.

Whereas many pathogens are fastidiously host specific, others, such as canine distemper (family Paramyxoviridae, genus *Morbillivirus*), may be transmitted across species boundaries. Wildlife may also acquire a foreign pathogen from their domesticated counterparts. A significant level of mortality can occur if an exotic pathogenic microorganism is introduced into a naive susceptible population (Anderson 1995; Roelke-Parker et al. 1996). Mathematical models based on dynamics and structure of the susceptible species, and on pathogenic processes and transmission properties of the pathogen, are invaluable in assessing risk of introduced pathogens to host population survival.

In general, infectious agents are relatively easy to identify genetically and serologically. Many diagnostic laboratory techniques are available for assisting conservation biologists with disease study. In vitro investigation is perhaps one of the most useful tools in ascertaining pathogen-host interaction. In vitro studies must, however, be complemented by observations on the natural course of infection in the species of interest to provide meaningful results. Data collection that assists field researchers in determining the health profile of a species or community should be incorporated in the research methodology. Much of this information can be gathered through direct field observation of behavior and mortality. Where possible, blood and other body fluid samples of all animals that are immobilized for any reason should be obtained. Collection and detailed evaluation of tissues from mortalities are also critical.

By learning the pathobiology of infectious agents, new areas of conservation application can be gained. The story of bovine brucellosis in bison (*Bison bison*) in Yellowstone National Park represents one example of the need for disease ecological research in wildlife management. Over one thousand bison have been culled in northern Yellowstone Park in order to prevent transmission of brucellosis from bison to livestock. In North America, brucellosis is a disease that causes infertility and abortion in cattle, elk (*Cervus elaphus*), and bison. Cattle and elk more often show these clinical signs; the disease does not usually affect bison. Initially introduced into bison from cattle, brucellosis has been virtually eradicated in Montana's livestock, leaving bison in Yellowstone as a potential reservoir of the disease. Around 50 percent of Yellowstone's bison herd may be infected. Management practices to date have focused on adhering to government protocols on brucellosis-free certification within livestock. This provides a substantial economic benefit to livestock growers.

Nevertheless, there is still a relative lack of knowledge about the transmissibility of the bacterial infectious agent *Brucella abortus* between domestic cattle and wildlife in free-ranging situations (Zaugg et al. 1993; Williams et al. 1993; Meagher and Meyer 1994; Dobson and Meagher 1996; Roffe et al. 1999). The conservation implications are profound because the bison story encapsulates many of the issues conservation biologists must grapple with today: introduced alien species (in this case a pathogen); growing conflicts between humans, their domesticated animals, and wildlife; and increased population impacts of disease through cross-species transmission (brucellosis may be shared between resident Yellowstone bison and elk populations). With elk winter feeding stations concentrating animals, the management of one species obviously impacts another. Brucella is also a zoonotic organism capable of causing infection in people—although rare. More so, the brucellosis story is a shining example of the increasingly complex public policy arena facing conservation managers as they grapple with disease and health issues.

Putting Pathogens to Conservation Work: Potential Biomarkers

Beyond the health ramifications of disease, pathogens can also serve as potential tools for studying the ecology of populations and individuals. Understanding of disease-causing organisms and the pathogenesis of disease has markedly increased due to the availability of molecular tools. For instance, information gained from studies of the Retroviridae, the family of RNA viruses that include the human immunodeficiency virus (HIV), feline leukemia virus (FeLV), feline immunodeficiency virus (FIV), simian immunodeficiency virus (SIV), and others show how the specific biology of a pathogen can provide a specific signature of infection and evolution (Levy 1993; Leitner et al. 1996; Gao et al. 1999; Poss and Overbaugh 1999; Hahn et al. 2000).

Of specific interest are efforts relating viral genetic diversity with population structure of the host. Many of the retroviruses, like other viruses, have potential evolutionary rates approximately one million times higher than those of their vertebrate hosts (Ricchetti and Buc 1990). This suggests that viruses circulating in one population will be genetically distinct from those circulating in a different population (which has been well documented with HIV in humans) (Bachmann et al. 1994; Louwagie et al 1995). Furthermore, adjacent populations that exchange infected individuals can be distinguished from those that do not by examining the genetics of the resident viruses. In the former case the virus population will be randomly distributed, while in the latter phylogenetic reconstruction of virus sequences will indicate distinct viral subpopulations (Poss and Overbaugh 1999). There is great potential benefit to applying these principles to wildlife species, as very recent changes in population dynamics are likely to be discernible due to rapid evolution of the viral genome.

By measuring viral genetic changes, we have the potential to use information that is used to determine contact and transmission of diseases between individuals and populations to delineate metapopulation dynamics of certain species such as mountain lions and lynx. This information can assist conservation managers in the determination of wildlife corridors and linkage areas and zones of wildlife and domestic animal contact.

Research Priorities in Conservation Medicine: Looking 10 Years Ahead

Disease affects every issue of concern to conservation biologists, including biodiversity, small or isolated population persistence, alien species introduction, and trophic cascades. Virtually any ecological perturbation that affects wildlife species can also alter the balance and composition of their pathogen communities. Future efforts in conservation need to incorporate the influence of disease on wildlife and of wildlife on disease. In this chapter, we provide key elements of a framework for inquiry that may assist conservation biologists in moving forward.

There are four broad areas for enhancement of the links between conservation biology and diseases of wildlife and humans:

1. *Expansion of interdisciplinary interaction.* Engage the talents of new disciplines to address conservation concerns. This can include the integration of conservation biology within existing disciplines such as veterinary and human medicine and social sciences such as economics (Rapport 1995). Medical and veterinary practitioners and researchers will certainly enrich their discipline by increasing their knowledge of how conservation issues such as biodiversity loss, climate and land-use change, and pollution influence human and animal health. Ecology and conservation biology become enriched when pathogens can be detected and their effects monitored.
2. *Integrated health and ecological assessment and monitoring.* Develop and refine environmental and physiological health assessment and monitoring protocols. The first step in conducting a current health assessment of an ecological system is to characterize the baseline health parameters for selected species or group of species (e.g., health indicator or sentinel species) and determine their responses to naturally fluctuating environmental variables. This includes monitoring variables that contribute to the physiological responses to stress within a population or in an individual (Hofer and East 1998). It will be necessary to establish normal values for bioindicator species based on (1) existing archived data; (2) data from processing of stored, unanalyzed samples where appropriate; (3) opportunistic collections of material from both pristine and disrupted ecosystems; (4) targeted collections of appropriate materials from healthy specimens reflecting that specific ecosystem; and (5) new monitoring efforts. The development of testing protocols, identification of suitable diagnostic procedures and tests, identification of laboratory support, development of a quality-control-assurance plan for laboratory results, and development of data management and data analysis plans are all required to conduct a thorough assessment.

   Sentinel species may assist in increasing monitoring efficiency at the ecosystem level. They can be utilized during rapid risk assessments to provide information on the environmental conditions of an area. Sentinel species or health indicator species can be selected for their ability to reflect environmental perturbations (Caro and O'Doherty 1999). Based on their life history and physiological attributes, selected species can provide insightful information about environmental changes at various spatial, temporal, and trophic scales. Given the complexity of ecosystems, sentinel species should be thought of as being specific to particular environmental conditions. In some cases, an assemblage of species may be suitable for providing an umbrella effect in monitoring the cumulative impacts of multiple environmental variables.

   Beyond species- and population-oriented monitoring, ecological health information needs to be collected through ecosystem monitoring efforts, including long-term ecological monitoring. New research developments in determining ecological integrity should incorporate health assessment indicators (Karr and Chu 1995, 1999).
3. *Expanded diagnostic capability.* Present diagnostic efforts are focused on clinical testing of human or domestic animals. The potential for applying existing diagnostic capacity to health monitoring of wildlife species or those of conservation concern is relatively untapped. The limitation of financial resources has been a major barrier. Laboratory support for performing diagnostic testing in species other than humans and domesticated animals is minimal. Cross-species diagnostic testing, in which one laboratory can do comparative assessment of disease between species, is extremely rare and is usually found within a couple of national disease testing centers (e.g., USDA Research Labs, Centers for Disease Control, National Wildlife Health Center, and the Southeastern Cooperative Wildlife Disease Study).

   Diagnostic laboratory testing can play an important role in monitoring the health of wildlife populations. During health evaluations, testing is necessary to detect exposure to an agent (serology), to identify the agents that are endemic in a population (bacteriology or virology) or to determine the cause of a catastrophic event such as a die-off or disease outbreak (clinical pathology, gross

BOX 8.1. Potential Research Priorities That Link Disease, Ecology, and Conservation Biology

1. Investigate vector-borne zoonotic diseases (such as mosquito-borne West Nile virus and malaria, sand fly–borne leishmaniasis, tick-borne Lyme disease, and bug-borne Chagas' disease).
   - What biotic and abiotic factors regulate vector populations? *Rationale for investigation:* Predators, parasites, and competitors may influence the population density and growth rates of arthropod vectors. Similarly, vectors are often limited by extremes in temperature and humidity, and those limitations may vary with life stage of the vector.
   - How do changes in climate influence vector populations, through either biotic or abiotic pathways? *Rationale for investigation:* Global climate change may influence both abundance and large- and small-scale distribution of vectors.
   - How do changes in land use influence vector populations, through either biotic or abiotic pathways? *Rationale for investigation:* Habitat destruction, conversion, and fragmentation may influence vectors directly or via their hosts or natural enemies, thereby affecting population size and variability.
   - What abiotic and biotic factors influence the proportion of vectors that are infected by the pathogen? *Rationale for investigation:* A key risk factor for many vector-borne diseases is the infection prevalence in the vector population. This can be influenced by abiotic factors that affect pathogen development and by ecological factors that affect the relative abundance of host species, which often vary in their competence as reservoirs for pathogens.
   - How does biodiversity affect disease risk? *Rationale for investigation:* High genetic or species diversity in the (reservoir) host community has recently been shown to reduce disease incidence in both human and crop systems.
2. Investigate directly transmitted zoonotic diseases (such as hantavirus pulmonary syndrome, Lassa fever and other arenaviral diseases, *Bartonella*).
   - What factors regulate reservoir populations? *Rationale for investigation:* For many directly transmitted zoonoses, rodents are the primary reservoirs. Rodent populations may be regulated by resource levels, predators, competitors, or pathogens (although most zoonotic pathogens appear relatively benign in reservoir hosts).
   - How do reservoir populations respond to changing climate, land use, and biodiversity? *Rationale for investigation:* Climate, land use, and diversity may influence reservoirs either directly, by allowing expansion or contraction of geographic ranges or population sizes, or indirectly, by influencing biota that regulate reservoir populations.
   - How does biodiversity in vertebrate communities affect disease risk? *Rationale for investigation:* High genetic or species diversity within vertebrate communities may regulate populations of reservoir species or otherwise reduce the probability of pathogen transmission.
   - How do local and global patterns of transportation influence the distribution of pathogens? *Rationale for investigation:* Travel by people and movements of ships and planes worldwide may introduce pathogens and their reservoirs or vectors to new areas.
3. Investigate water-borne and food-borne zoonotic diseases (such as *Vibrio* cholera, marine biotoxins and cyanobacteria, *Salmonella, Campylobacter*).
   - How do changes in global temperature influence populations of pathogens, either free-living or commensal with other aquatic organisms? *Rationale for investigation:* Population growth of many water-borne pathogens is sensitive to water temperature, as is population growth of planktonic organisms with which pathogens may associate (e.g., *Vibrio cholerae*).
   - How do influxes of nutrients to lakes and estuaries influence populations of pathogens, either free-living or commensal with other aquatic organisms? *Rationale for investigation:* Population growth of many water-borne pathogens is sensitive to nutrient concentrations (e.g., nitrogen, phosphorus), as is population growth of planktonic organisms with which pathogens may associate. Human activities, such as livestock production, agriculture, and septic leakage, are often responsible for production and release of these nutrients.
4. Investigate noninfectious diseases (such as chronic and acute toxic effects of environmental contaminants; asthma; malignant tumors).
   - To what degree are wildlife populations, especially those of conservation concern, affected by pollutants that decrease viability or reproductive success? *Rationale for investigation:* Evidence is mounting that sublethal effects of pollutants (e.g., endocrine mimics) can reduce population viability.
   - How do noninfectious diseases interact in wildlife populations? *Rationale for investigation:* Noninfectious agents may reduce effectiveness of the immune system, thereby influencing the ability of organisms to resist other environmental insults.

Sources: Ostfield and Keesing 2000a; Zhu et al 2000.

pathology, histopathology). Tests can be used for epizootic and epidemiologic purposes and can estimate prevalence, incidence, and geographic distribution of selected disease agents; determine infection in subpopulations; and delineate intra- and interspecific disease transmission. The results of diagnostic testing are most useful in complementing thorough field-based ecological research. Ecological studies provide the necessary context for any results concerning disease dynamics and can even discern certain physiological responses due to stress imposed on populations by environmental change (Hofer and East 1998).

4. *Resolution of human and wildlife conflict—implementing conservation medicine practice in conservation reserve design and management.* With increasing fragmentation of habitat, the consequences of enhanced human and animal conflicts are more apparent. Disease is only one manifestation of this global phenomenon. Nevertheless, conservation managers need to be savvy in developing management scenarios that minimize disease impacts. Buffer zones and wildlife corridors may require new designs to mitigate or diminish disease threats. Resolving human and wildlife conflicts is the challenge ahead in conservation. Those conflicts include the interaction between domesticated animals and wildlife. With growing intrusions of people and their animals into wildland areas, such as livestock grazing on public lands, salmon aquaculture pens in coastal marine areas, primate ecotourism in the tropics, and the influx of backpackers with their dogs into designated wilderness areas, disease mitigation will be a major factor in conservation management. The design and management of conservation reserves need to be open to the consequences of disease threats—not as a marginal issue of concern, which is the case at this time, but as an issue more central to achieving long-term conservation success.

Conclusions

For many of the research questions presented in this chapter, answers will come from a combination of monitoring, modeling, experimentation, and comparison. Monitoring is crucial for detecting changes in disease distribution or incidence as a result of human-caused changes in climate, land use, or pollutant concentration. For example, surveillance for diseases using sentinel animals can provide advance warning of changes in distribution or virulence of pathogens, and suggest possible causes. Modeling allows exceedingly complex parts of nature to be abstracted; relationships among populations, species, habitats, and ecosystems to be specified; the logic of interactions to be clarified; and specific hypotheses to be derived. Experimentation is important for testing specific hypotheses on relatively small scales, and for determining mechanisms for observed patterns at larger scales or within more complex, inclusive systems. For instance, effects of biodiversity or habitat destruction

on the maintenance and transmission of pathogens can be examined in a laboratory setting by experimentally altering diversity or landscape patterns and measuring responses.

Comparative methods are analogous to experiments but consist of monitoring effects of conditions that have not been experimentally manipulated and differ between systems in specific ways. For example, population dynamics of an imperiled species can be monitored before and after a toxic spill, or inside and outside an area where a pathogen has invaded. Effects of diminishing biodiversity on vector-borne vs. directly transmitted diseases may elucidate the influence of transmission mode on ecology of infectious diseases.

Ecological studies of infectious and noninfectious diseases are therefore crucial to understanding, predicting, and reducing risk to the health of humans, domesticated animals, and wildlife and the environment that sustains them. Conservation medicine can provide new skill sets to address disease impacts in conservation. These include the incorporation of biomedical research and resources in conservation problem solving; the development of diagnostic methods that examine ecological and health parameters; and the design and implementation of integrated health and ecological assessment models.

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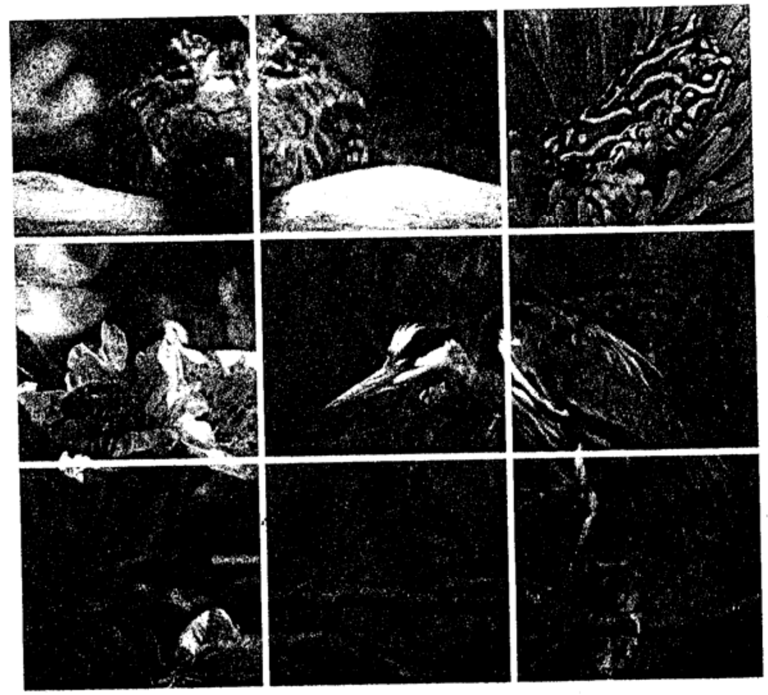
Conservation biology : research priorities for the next decade / edited by Michael E. Soulé and Gordon H. Orians.
p. cm.
Includes bibliographical references.
ISBN 1-55963-868-0 (cloth : alk. paper) — ISBN 1-55963-869-9 (pbk. : alk. paper)
1. Conservation biology—Research. I. Soulé, Michael E. II. Orians, Gordon H.
QH75 .C6616 2001
333.95'16—dc21
2001003355

British Cataloguing-in-Publication Data available.

Printed on recycled, acid-free paper

Manufactured in the United States of America
10 9 8 7 6 5 4 3 2 1

CONSERVATION BIOLOGY



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Society for Conservation Biology

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