

But how well do these new observations fit with the predictions of global climate models (GCMs)? The positive feedbacks on global warming stemming from the reduction in snow cover are already included within GCMs. Nearly all of the models include representations of the physics of land-surface processes, including the energy, moisture, and momentum balance among vegetation, soil, snow, and the atmosphere. As a result, GCMs show strong warming in the polar region; in these areas, the simulated warming is amplified through albedo feedbacks from reduced snow and ice.

Unfortunately, few GCMs represent the possible feedbacks from changing vegetation cover and the associated changes in land-surface properties. As Chapin *et al.* suggest, increases in shrub and forest cover in the Arctic could dramatically amplify global warming in the Arctic, but nearly all GCMs used today do not consider such changes in vegetation cover. However, a study by Levis *et al.* (4) used one of the few fully coupled global climate-vegetation models to estimate the potential for vegeta-

tion feedbacks on Arctic climate. They concluded that the northward shift of trees and shrubs induced by global warming would raise seasonal temperatures by an additional 1.1° to 1.6°C in spring. Naturally, further investigations with alternative models of climate-vegetation interactions are needed to corroborate this kind of result. But Chapin *et al.* have now provided us with strong empirical evidence to support this hypothesis.

In a way, the Arctic may be the “canary in the coal mine” of our global climate system. Climate theory and models have both suggested that the Arctic region will experience some of the strongest effects of global warming, mainly because of the large magnifying effects of snow, ice, and (possibly) vegetation feedbacks. And now several sources of evidence are showing that not only is the Arctic warming, but also that the feedback mechanisms seem to be kicking into high gear.

Ultimately, this research leads one to wonder whether the Arctic is headed toward a fundamentally different climatic regime—one with much less snow, much less sea ice, and possibly more shrubs and

forest. Furthermore, scientists and decision-makers must ask what this radically different climate future means for the species and peoples that call the Arctic home today, including polar bears, seals, and Inuit communities. And given the massive inertia of the global climate system—with the significant degree of additional warming already “in the pipeline,” even if CO₂ levels were to stabilize today (5)—combined with the difficulty of achieving drastic decreases in greenhouse emissions anytime in the near future, one also has to ask: Is the Arctic we know today already lost? To answer these questions, studies like that of Chapin *et al.* demand more attention.

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VIROLOGY

What Links Bats to Emerging Infectious Diseases?

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Three species of horseshoe bats (*Rhinolophus* spp.) have now been officially recorded as the natural reservoir host of the coronavirus that causes severe acute respiratory syndrome (SARS) [see the report by Li *et al.* on page 676 of this issue (1) and the report by Lau *et al.* (2)]. The emergence of this pathogen (SARS-CoV) in southern China in 2002–2003 almost brought the burgeoning economy of Southeast Asia to its knees (3, 4). Bats are now known to be natural reservoir hosts to several other new emergent disease pathogens: Nipah and Hendra viruses (5) and potentially Ebola and Marburg viruses. They are also reservoirs to “older” and more well-known pathogens, such as rabies virus, which frequently resurge into human populations or domestic livestock. Fieldwork on SARS illustrates not only the crucial role that conservation organizations play in frontline research on emergent diseases, but also the shortcomings in our understanding of the etiology of these diseases.

A key step in determining the threat imposed by new pathogens is identifying the route along which they are transmitted from their reservoir to new hosts such as domestic livestock or humans. In the case of pathogens that use bats as reservoirs, a common route seems likely. Bats’ feeding habits are constrained by the aerodynamics of flight, so they can’t ingest huge amounts of food. Yet many bats are frugivorous—that is, they meet their energy requirements by ingesting fruits. But instead of swallowing them, they chew them to extract the sugars and higher energy components, and then spit out the partially digested fruits, which drop to the ground. Other animal species can ingest these fruit remnants and may consequently become infected with virus particles in residual bat saliva. A small variant on this is required in the case of the insectivorous *Rhinolophus* bat species, but they also discard the heavier body parts of the insects they eat, which are then ingested by terrestrial foraging species. This provides a route for SARS-CoV to be infrequently transmitted to masked palm civets (*Paguma larvata*), the animals that were

initially considered to be the potential virus reservoirs in the SARS epidemics. It would also explain how gorillas, chimpanzees, and duikers acquire Ebola virus during seasonal fruiting events when bats and primates feed in or below fruit-bearing trees. The animal pens of the pig farms where the Nipah virus outbreak in Malaysia was first reported were littered with partially digested fruits that were regurgitated from bats. Similar observations were reported at the site of the Hendra virus outbreak in Queensland, Australia. In Bangladesh, the Nipah virus has been shown to be transmitted directly from bats to humans. There, during the fruiting season, young boys climb trees to pick fruit. They frequently add fruit that is partially chewed by bats to their collections, which they then sell to the local salesmen. The fruit is pulped to produce a drink that is sold in neighboring villages. The Nipah outbreaks there often follow the trails of these bicycle-borne salesmen (6).

The transmission dynamics of these emerging viruses can be readily modeled in a framework originally developed to examine the rate of spread of HIV-AIDS in populations with heterogeneous mixing of people with different levels of sexual activity (7). The key difference with using this approach to examine emergent diseases is that transmission of emergent pathogens between populations tends to be unidirectional (8). Thus, bats transmit SARS-CoV to palm civets, but not *vice versa*. This means that control of the disease has to

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focus on either controlling its abundance in its reservoir, preventing its spillover between hosts, or rapidly reducing its spread once it has infected humans or domestic livestock. This creates a dilemma for both public health and conservation biology: Should we attempt to control potentially emergent pathogens by focusing on their reservoir hosts, or should we try and prevent the spillover events that allow the pathogen to spread in a new population? A third option is to develop a vaccine to protect hosts in the spillover population. Unfortunately, because spillover is likely to be a random event, effective protection requires that all individuals in the spillover population become protected. We have never achieved this level



Bats, the great natural reservoir for viruses. Knowing more about bat ecology and immunology is crucial to controlling spillover of viruses and related diseases to humans.

of coverage for well-known pathogens that have fairly safe and effective vaccines (9).

The two viable alternatives are either to reduce the prevalence of the pathogen in the reservoir host, or to identify the conditions that lead to spillover and attempt to minimize these. The latter will involve surveying a diversity of wild species for potential pathogens and unraveling the changes in ecological conditions that lead to spillover events. In both these areas, conservation organizations seem to be playing almost as important a role as medical schools. This is both ironic and tragic given that conservation nongovernmental organizations have much smaller budgets and broader agendas than medical schools.

Is it unusual that so many emergent diseases use bats as reservoirs? What's special about bats? We often forget that bats form a sizable proportion of mammalian diversity; the 916 extant species constitute about 20% of this diversity (10). Thus, if all potential reservoirs were created equal, we would expect almost as many emergent pathogens from bats as from small mammals. This is not the case; less than 2% of human pathogens have bats as natural reservoirs [bats may be persistently infected, yet never display any pathologies (11)]. These data suggest that bats are not overrepresented in the numbers of pathogens that emerge from them. What is more conspicuous is the pronounced pathology of pathogens that spill over from bats and that most of these spillovers have occurred in the last 20 years. What might cause this?

One obvious difference between bats and other mammals is that bats fly. This means that they have hollow bones, as do birds. But bone marrow is where most mammals produce the B cells of the

immune system. Where do bats produce B cells? Unfortunately, we don't know enough about bat immunity to address this question. They may compensate by increasing B cell production in the marrow of their pelvis and legs, but we have little data on this. Bats are long-lived, highly gregarious, and can enter torpor. We do not know whether these traits allow these ancient mammals to differ from other mammals in the way they combat potential viral infections. Are there differences in the functionality or type of receptors required for infection? Are there bat antiviral proteins (interferons) that can stop viral replication as in other mammals, or do bats possess a mechanism to prevent their inactivation? Alternatively, we could ask if bats possess a novel innate immunity that allows them to cope with certain classes of viruses in ways that other mammals cannot. If the latter is the case, then what would studies of bat immunity tell us about new ways to attack and treat viral diseases? The literature is silent on this. Very few medical schools have experimental bat colonies, and work in this area may be a little "outside the box" for conservative funding agencies.

Knowing more about bats, and particularly more about bat ecology and immunology, is crucial if we are to develop new treatments and ways to control the viral diseases that are an increasing threat to humans. Assuming we can control these diseases by simply controlling bats is both naïve and short-sighted. Instead, we must recognize that increased rates of spillover-mediated pathogen transmission from bats to humans may simply reflect an increase in their contact through anthropogenic modification of the bat's natural environment. The emer-

gence of Nipah virus and SARS-CoV epitomizes this situation. In regions where large areas of bat habitat have been converted to agricultural land or oil palm plantations, the surviving bat populations will be concentrated in the remaining patches of forest that provide the resources they need. When these patches of fruit trees are used as shade for intensive animal husbandry, then it is highly likely that the fruits and insects chewed by bats will find their way into the human food chain.

The scientists who revealed the bat reservoir of SARS-CoV operate within a new intellectual paradigm. They call their discipline "conservation medicine" (12). It brings together the two areas of natural science that will be crucial to the future welfare of

humans: health sciences (human, veterinary, and plant pathology) and the ecological sciences that monitor the health of populations, communities, and ecosystems. The Millennium Ecosystem Assessment has emphasized the dependence of human health and economic well-being on goods and services provided by the natural environment (13). This dependence can only be actively capitalized upon if we increase our understanding of the population dynamics and ecology of new and old infectious diseases. Conservation medicine is an idea whose time has come none too soon.

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