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What is the Risk for Exposure to Vector-Borne Pathogens in United States National Parks?

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Abstract

United States national parks attract >275 million visitors annually and collectively present risk of exposure for staff and visitors to a wide range of arthropod vector species (most notably fleas, mosquitoes, and ticks) and their associated bacterial, protozoan, or viral pathogens. We assessed the current state of knowledge for risk of exposure to vector-borne pathogens in national parks through a review of relevant literature, including internal National Park Service documents and organismal databases. We conclude that, because of lack of systematic surveillance for vector-borne pathogens in national parks, the risk of pathogen exposure for staff and visitors is unclear. Existing data for vectors within national parks were not based on systematic collections and rarely include evaluation for pathogen infection. Extrapolation of human-based surveillance data from neighboring communities likely provides inaccurate estimates for national parks because landscape differences impact transmission of vector-borne pathogens and human-vector contact rates likely differ inside versus outside the parks because of differences in activities or behaviors. Vector-based pathogen surveillance holds promise to define when and where within national parks the risk of exposure to infected vectors is elevated. A pilot effort, including 5–10 strategic national parks, would greatly improve our understanding of the scope and magnitude of vector-borne pathogen transmission in these high-use public settings. Such efforts also will support messaging to promote personal protection measures and inform park visitors and staff of their responsibility for personal protection, which the National Park Service preservation mission dictates as the core strategy to reduce exposure to vector-borne pathogens in national parks.

Keywords

flea; mosquito; national park; tick; vector-borne disease

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The 397 National Park Service (NPS) units of the United States (hereafter referred to as national parks) attract 275 million visitors annually (http://www.nature.nps.gov/stats/). The majority of visits occur during the warm months, when arthropod vectors of human pathogens, such as fleas, mosquitoes, and ticks, are most active. Park visitors frequently engage in outdoor activities that potentially place them at risk for exposure to these vectors and the pathogens they transmit. However, the magnitude of this public health problem in the national parks remains unknown. This results from a lack of systematic surveillance in national parks for arthropod vectors and the pathogens they carry, combined with a lack of detailed travel histories collected during case investigations for notifiable vector-borne diseases, with the notable exception of plague, that could implicate a national park as a potential or likely source of infection (Eisen and Eisen 2007). Surrounding areas cannot be assumed to represent the risk within a national park because 1) landscape differences between the relatively undisturbed ecosystems within the parks and fragmented populated areas outside the parks may impact enzootic transmission of vector-borne pathogens and 2) potential differences in activities or behaviors between park visitors and residents of surrounding areas could affect contact rates with vectors.

To reduce risk of human exposure to vector-borne pathogens within the national parks, it is essential to first define to what extent vector-borne pathogens occur in the parks, and when and where within the parks the risk for exposure to infected vectors is elevated versus low. Such knowledge will facilitate improved messaging to visitors and staff regarding their risk of exposure to vector-borne pathogens and the need for use of personal protection measures and/or activity modification. Should an exceptional situation arise, such as a major outbreak of a potentially severe vector-borne disease within a national park, prior knowledge of the areas and time periods presenting the highest risk of exposure to the causative agent also would help to optimally target potential NPS-approved response activities in space and time, thus reducing the potential for human–vector contact while minimizing the impacts on the ecosystem of the park. This is in keeping with balancing the NPS preservation mission (to protect all resources and leave them unimpaired for the enjoyment of future generations) against the need to protect against a significant threat to human safety (National Park Service 2006).

Key Vectors and Vector-Borne Pathogens Potentially Occurring in U.S. National Parks

At a national scale in the United States, the broad geographic distributions of important vector species are well documented (Eskey and Haas 1940, Dennis et al. 1998, Brown et al. 2005, Darsie and Ward 2005; http://vectormap.org/). However, within these broad geographic ranges the risk of encountering vectors, and infected vectors, may vary substantially even over short distances. This is especially relevant within ecologically or climatically heterogeneous areas, including some of the larger national parks. Because national parks are distributed across the United States, they collectively present risk to a wide range of vector species, and numerous vector-borne bacterial, protozoan or viral pathogens (Table 1). Below, we summarize the most important vectors and vector-borne pathogens by region of the United States. However, we caution that local vector and pathogen surveillance is required to determine the abundance of vectors and prevalence of vector-borne pathogens within any given national park. As outlined in the next section, such data are scarce from U.S. national parks and existing vector databases do not contain information to support risk assessments for exposure to vector-borne pathogens in the parks.

For tick vectors and tick-borne diseases, national parks in the eastern United States may harbor multiple species of human-biting hard (ixodid) ticks and present risk for exposure to a wide range of human pathogens. The blacklegged tick (*Ixodes scapularis* Say) is abundant in the northeastern and north–central United States, and is the principal vector to humans of multiple pathogens including the bacterial agents causing Lyme disease (*Borrelia burgdorferi*) and human granulocytic anaplasmosis (*Anaplasma phagocytophilum*), and a protozoan causing babesiosis (*Babesia microti*) (Sonenshine 1993, Dennis et al. 1998, Brown et al. 2005, Piesman and Eisen 2008). It also can transmit the bacterial agent causing tularemia (*Francisella tularensis*) and the Powassan virus (Eisen 2007, Ebel 2010). Two other commonly human-biting ticks occur in the eastern United States: the American dog tick (*Dermacentor variabilis* (Say)) and the lone star tick (*Amblyomma americanum* (L.)). The American dog tick is a vector to humans of multiple bacterial agents, including those causing Rocky Mountain spotted fever (*Rickettsia rickettsii*) and tularemia (Sonenshine 1993, Brown et al. 2005, Eisen 2007). The bite of this tick also may cause tick paralysis because of a toxin present in its saliva (McCue et al. 1948, Ransmeier 1949). The lone star tick is the primary vector to humans of the causative agent of human monocytic ehrlichiosis (*Ehrlichia chaffeensis*), and also may be involved in the transmission of the agents of Rocky Mountain spotted fever, spotted fever rickettsiosis caused by *Rickettsia parkeri* (together with the Gulf Coast tick, *Amblyomma maculatum* Koch), and tularemia (Sonenshine 1993, Childs and Paddock 2003, Brown et al. 2005, Eisen 2007). Human-biting life stages of these three tick species are abundant in the late spring and summer (Sonenshine 1993, Eisen 2007), coinciding with heavy visitation of the eastern parks, and can be encountered through contact with emergent vegetation.

National parks in the intermountain west harbor the human-biting Rocky Mountain wood tick (*Dermacentor andersoni* Stiles), which is a vector of the causative agents of Rocky Mountain spotted fever and tularemia, and also of the Colorado tick fever virus (Sonenshine 1993, Brown et al. 2005, James et al. 2006, Eisen 2007). Rocky Mountain wood tick bites also may result in tick paralysis (Dworkin et al. 1999, Pape et al. 2006). One notable aspect of the biology of the Rocky Mountain wood tick is that the abundance of the human-biting adult stage peaks in the spring (James et al. 2006), and is in rapid decline by the summer peak in park visitation.

National parks in the far western United States may harbor the western blacklegged tick (*Ixodes pacificus* Cooley & Kohls) and the Pacific Coast tick (*Dermacentor occidentalis* Marx), and the Rocky Mountain wood tick and American dog tick also can be encountered in some areas (Dennis et al. 1998, Brown et al. 2005, James et al. 2006). The western blacklegged tick is the primary vector to humans in the far west of the causative agents of Lyme disease and human granulocytic anaplasmosis, and also may be involved in the transmission of a recently described protozoan disease agent (*Babesia duncani*) (Foley et al. 2004, Brown et al. 2005, Conrad et al. 2006). Most human infections likely result from exposure to the nymphal stage of this tick. Human-nymph contact is reduced in the west, compared with the closely related blacklegged tick in the east, because nymphs of the western blacklegged tick are 1) most abundant in the spring with declining numbers during the summer peak in park visitation and 2) reluctant to ascend emergent vegetation such as grass and brush, which restricts the substrates where humans readily contact nymphs to leaf litter and fallen logs (Clover and Lane 1995, Lane et al. 2004). The Pacific Coast tick is a potential vector of the agents causing Rocky Mountain spotted fever and Colorado tick fever, and also may be involved in the transmission of a recently described rickettsial disease agent provisionally named *Rickettsia* 364D (Brown et al. 2005, Shapiro et al. 2010).

Sleeping in cabins, particularly in the national parks in the west, also may present risk for exposure to soft (argasid) ticks and their associated relapsing fever spirochetes (United States Centers for Disease Control and Prevention [CDC] 1973, 1991; Boyer et al. 1977; World Health Organization [WHO] 1991; Paul et al. 2002). The tick *Ornithodoros hermsi* Wheeler transmits the relapsing fever spirochete *Borrelia hermsii* in mountainous areas of the west, and visits to lower elevation areas in the southwest can result in exposure to *Ornithodoros turicata* (Duges), which transmits *Borrelia turicatae* (Dworkin et al. 2002, Barbour 2005). Notable outbreaks of tick-borne relapsing fever in staff and visitors occurred in Grand Canyon National Park in 1973 (>60 confirmed or probable cases) and 1990 (17 confirmed or probable cases) (Boyer et al. 1977, Paul et al. 2002).

Visits to national parks also may result in exposure to human-biting mosquitoes and their associated arboviruses. West Nile virus is now present throughout the contiguous United States, and exposure can occur through the bites of different mosquito species (Kramer et al. 2008). The most prominent mosquito vectors of West Nile virus to humans include: *Culex pipiens* L. (northern United States), *Culex nigripalpis* Theobald (southeastern United States), *Culex quinquefasciatus* Say (southern United States), *Culex salinarius* Coquillett (eastern United States), and *Culex tarsalis* Coquillett (western United States and Central Plains). Less common mosquito-borne arboviruses with potential for exposure in national parks include eastern equine encephalitis virus (primarily in the Atlantic and Gulf Coast states), La Crosse encephalitis virus (upper Midwestern and mid-Atlantic and southeastern states), St. Louis encephalitis virus (eastern United States and Central Plains), and western equine encephalitis virus (western United States and Central Plains) (Moore et al. 1993; http://www.cdc.gov/ncidod/dvbid/arbor/). Several mosquito species are involved in the transmission of these viruses to humans, including *Aedes triseriatus* (Say) (La Crosse encephalitis virus) and different *Culex* spp. mosquitoes (Saint Louis encephalitis virus and western equine encephalitis virus).

In parks located west of the 100th meridian (that bisects the Dakotas, Nebraska, Kansas, Oklahoma, and Texas) national park staff and visitors also may encounter the plague bacterium, *Yersinia pestis.* Transmission can occur through direct contact with infected animals or via exposure to infected fleas (Barnes 1982). *Oropsylla montana* (Baker) and *Eumolpianus eumolpi* (Rothschild), ground squirrel- and chipmunk-associated fleas, respectively, are arguably the most common bridging vectors to humans (Nelson 1980, Eisen et al. 2006, Lowell et al. 2009) but numerous other rodent-associated fleas can serve as vectors of plague bacteria (Eisen et al. 2009). Human plague cases with exposure to *Y.*

pestis occurring in a U.S. national park include a visitor to Sequoia National Park in 1984 (CDC, unpublished data), a NPS biologist in Petrified Forest National Park in 1995 (Levy and Gage 1999, CDC unpublished data), and a recent fatal case, after exposure to a plague-infected mountain lion, in a NPS biologist in Grand Canyon National Park in 2007 (Wong et al. 2009).

Objectives

We aimed to assess the current state of knowledge for risk of exposure to vector-borne pathogens in national parks and to propose strategies to improve pathogen surveillance and reduce human pathogen exposure. It also should be noted that the problem of risk assessment for vector-borne diseases, and the potential solutions discussed herein to reduce such risks, are not unique to U.S. national parks but can be applied broadly to other public lands, particularly those with a similar conservation focus, including national forests, wildlife preserves, and state, regional, and local parks worldwide.

Existing Information for Vectors and Vector-Borne Pathogens Within U.S. National Parks

Peer-Reviewed Literature

We conducted a literature search, using the Web of Knowledge (v.5.5.), based on the topic words flea, mosquito, or tick combined with national battlefield, national historic, national historical, national lakeshore, national memorial, national military, national monument, national park, national preserve, national recreation, national reserve, national river, national seashore, national trail or parkway. This produced 16, 10, and 7 records, respectively, with information from U.S. national parks or other types of NPS units and potential relevance to tick-borne diseases, mosquito-borne diseases, or flea-borne diseases (i.e., plague in the western United States). Six of the 16 tick-related records addressed the Rocky Mountain wood tick in Rocky Mountain National Park, including studies on the ecology of Colorado tick fever virus during an outbreak of Colorado tick fever among park visitors in the early 1970s (Carey et al. 1980; Bowen et al. 1981; McLean et al. 1981, 1989, 1993a) and a recent study on the tick's life history (Eisen et al. 2008). Other studies dealt with outbreaks of relapsing fever in Grand Canyon National Park (Boyer et al. 1977, Paul et al. 2002), the life history of the blacklegged tick in Morristown National Historical Park or along the Appalachian Trail (Vail and Smith 1997, 1998; Oliver and Howard 1998), tick-host-pathogen associations on Cape Hatteras National Seashore and Assateague Island National Seashore (Oliver et al. 1999), surveys for ticks and tick-borne pathogens in Yosemite National Park (Schwan et al. 1993, Fleer et al. 2011), and surveys for ectoparasites on vertebrates in Big South Fork National River and Recreation Area and Great Smoky Mountains National Park (Reeves et al. 2007, Parker et al. 2009). Other relevant studies, not recovered in the search but known to us, reported on the detection of *E. chaffeensis* from *A. americanum* ticks collected on Fire Island National Seashore (Mixson et al. 2006) and public education and Lyme disease prevention in the Delaware Water Gap National Recreation Area (Hakim and Bitto 2005).

The mosquito records revealed by the search included summaries of mosquitoes encountered in Glacier National Park, Grand Teton National Park, Great Smoky Mountains National Park, Kings Canyon National Park, Sequoia National Park, Yellowstone National Park, or Yosemite National Park (Nielsen and Blackmore 1996; Moore 2001; Reeves et al. 2004; Nielsen 2009, 2012; Holmquist et al. 2011). Some of these studies were based on larval collections, with no special effort to collect the adult stage of human-biting mosquitoes, and none examined collected mosquito specimens for presence of human pathogens. Other studies addressed the life history of *Culex quinquefasciatus* in Hawai'i Volcanoes National Park and Haleakala National Park (Aruch et al. 2007, Reiter and Lapointe 2009), use of repellents against the black salt marsh mosquito (*Aedes taeniorhynchus* (Wiedemann)) in Everglades National Park (Barnard et al. 2002), and use of different attractants for traps to collect mosquitoes in Everglades National Park (Kline et al. 1991). The flea records included summaries of fleas encountered on rodents in Big South Fork National River and Recreation Area, Grand Teton National Park, Rocky Mountain National Park, or Yosemite National Park (Eads and Campos 1983, Watkins et al. 2006, Parker et al. 2009, Fleer et al. 2011), and studies of flea-rodent-*Y. pestis* interactions in Lava Beds National Monument and Crater Lake National Park (Stark and Kinney 1969, Nelson and Smith 1976, Smith et al. 2010). Other relevant studies, not recovered in the search, reported on fleas encountered in Crater Lake National Park and Mesa Verde National Park (Beck 1966, Gresbrink and Hopkins 1982).

Further searches were conducted that combined topic words for pathogens (*Anaplasma, Babesia, Borrelia, Ehrlichia, Francisella, Rickettsia, Yersinia*, or virus) with the different types of NPS units. These searches produced six additional articles dealing with detection of pathogens in vertebrates, including the isolation of *B. burgdorferi* from a bird captured in the Saint Croix National Scenic Riverway (McLean et al. 1993b), detection of *B. microti* from rodents in Grand Teton National Park (Watkins et al. 1991), serological evidence for exposure of cervids captured or shot in national parks in California to *B. burgdorferi* (Yosemite National Park) or *A. phagocytophilum* (Point Reyes National Seashore) (Aguirre et al. 1995, Foley et al. 1998) and serological evidence for exposure of carnivores captured in Yellowstone National Park to *F. tularensis* (coyotes) or *Y. pestis* (cougars and coyotes) (Gese et al. 1997, Biek et al. 2006).

Finally, a recently published study on zoonotic infections among employees at Great Smoky Mountains National Park and Rocky Mountain National Park provided serologic evidence of previous exposure to various tick- or mosquito-borne pathogens, including *A. phagocytophilum*, Colorado tick fever virus, *E. chaffeensis*, La Crosse virus and West Nile virus, and of infection during a 1-yr prospective study with mosquito-borne La Crosse virus in an employee at Great Smoky Mountains National Park (Adjemian et al. 2012). However, it is not clear to what extent these exposures occurred within the National Parks versus elsewhere.

Technical Reports and Databases

There also is a "gray literature," that is, internal NPS technical reports and CDC and state health department internal records, as well as various databases containing vector collection records. However, many of these sources are not readily accessible and generally unavailable to decision makers who want to know about previous disease outbreaks. An examination of NPS technical reports published from 2004 to 2012 produced reports on mosquito risk assessment in Everglades National Park and the risk for exposure to mosquito- or tick-borne pathogens on Fire Island National Seashore and in national parks in California (Ginsberg 2005, Leong 2010, National Park Service and California Department of Public Health 2011). NPS species databases focus primarily on vertebrates and contain scant information on arthropod vectors or associated human pathogens. External databases, such as the Global Biodiversity Information Facility (http://www.gbif.org/), the Walter Reed Biosystematics Unit's Vector-Map (http://vectormap.org/), the Centers for Disease Control and Prevention's ArboNet (http://www.cdc.gov/ncidod/dvbid/westnile/USGS_frame.html), or the U.S. Department of Agriculture's tick geodatabase, could potentially be mined for data relating to arthropod vectors in national parks. However, because the information contained in these databases represent compilations of vector collections generated without a systematic sampling design and may span decades, it is not adequate for the purpose of assessing risk of exposure to vector-borne pathogens in national parks.

Assessment of the Quality of the Existing Information

We have noted previously that risk assessments for exposure to vectors or vector-borne pathogens, including mapping, or modeling outputs, are only as good as the data on which they are based (Eisen and Eisen 2011). Existing data from U.S. national parks are not adequate to support high-quality risk assessments for vector-borne pathogens or messaging to park staff and visitors regarding their risk of pathogen exposure beyond very general statements, such as the following hypothetical example statement: While visiting this park you may encounter the tick *Dermacentor andersoni*, which bites humans and is known to be capable of transmitting several human pathogens including those causing Colorado tick fever, Rocky Mountain spotted fever, and tularemia. Basic measures for which existing information is lacking or inadequate for most national parks include 1) presence by individual national park of specific vector species and, most importantly, vector-borne pathogens, 2) high risk areas within the parks, and 3) high risk periods of the year. Such knowledge simply cannot be generated without a systematic surveillance effort. We recognize that systematic surveillance programs to produce such information also are lacking for tick- and flea-borne pathogens in the United States *outside* of the national parks, as well as for mosquito-borne pathogens in many populated areas. However, it is important to remember that, in populated settings, human-based surveillance provides information on areas where risk of exposure to (notifiable) vector-borne pathogens is greatest. National parks, and other public lands visited frequently by travelers and nonresidents, therefore present a unique problem where the local epidemiology may not accurately reflect the risk for vector-borne pathogen transmission in these environments. We also note a lack of long-term data on vector, pathogen, or disease occurrence from the national parks; disease outbreaks can spur intensive short-term activities but longer term studies are lacking. This is unfortunate because, due to the relative stability of their ecosystems and land use patterns, national parks are exceptionally well suited for studies on how climate change may impact the distribution and abundance of mosquito and tick vectors, and the occurrence and prevalence of their associated pathogens.

Toward Improved Surveillance for Vectors and Vector-Borne Pathogens in U.S. National Parks

Uniqueness of National Parks Compared With Neighboring Areas

Positive spatial autocorrelation, with high values tending to be geographic neighbors of high values (e.g., a county with high Lyme disease incidence neighboring on other counties with high Lyme disease incidence) and low values geographic neighbors of low values, is commonly observed for risk measures relating to mosquito or tick vectors or vector-borne diseases (Eisen and Eisen 2011). This can be exploited for spatial extrapolation of risk measures from an examined geographic area to neighboring nonsampled areas. However, national parks are problematic with respect to this approach because they almost always harbor unique and relatively undisturbed ecosystems. They also may be less fragmented compared with neighboring areas, a factor potentially impacting species composition and abundance of vertebrate reservoirs/amplification hosts of mosquito- or tick-borne pathogens and the intensity of enzootic pathogen transmission (Eisen et al. 2012, Wood and Lafferty 2013). Thus, the ecology of a vector-borne pathogen may differ substantially when comparing a national park to its neighboring areas. This could result in microhabitat patterns of risk for exposure to infected vectors that are unique to the park environment and distinct from those found just outside the park. To further complicate the issue, human use of the park environment (hiking and spending large portions of time outdoors) may result in increased risk of vector exposure compared with the use of surrounding areas; thus, even if vector-based risk measures are equivalent between a national park and its neighboring lands, human behavior may lead to increased risk of pathogen exposure in the park. The situation in neighboring areas therefore cannot be assumed to reflect the risk of exposure to vector-borne pathogens in a national park, regardless of whether the data were based on entomologically or epidemiologically derived risk measures.

Vector-Based Surveillance Within National Parks

National parks can readily be surveyed for risk of contact with human-biting ticks and mosquitoes, and their associated pathogens (Ginsberg 2005). Standard collection methodologies for host-seeking hard ticks (dragging/flagging of vegetation), soft ticks (carbon dioxide-baited ground traps), or mosquitoes (battery-operated traps suspended from brush or trees) have minimal environmental impacts and are well suited for use in a national park. Pathogen detection in collected ticks or mosquitoes can be achieved following established polymerase chain reaction (PCR)/RT-PCR protocols. Risk measures can then be generated based on vector abundance (e.g., number of ticks encountered per minute of drag sampling or number of mosquitoes per trap-night) or pathogen infection (prevalence of infection among examined specimens). Ideally, they should be presented as a more informative combination measure, such as the number of infected ticks encountered per minute of drag sampling or unit of sampled area (referred to as acarological risk index) or the number of infected female mosquitoes collected per trap night (sometimes referred to as the vector index) (Eisen and Eisen 2008). Spatial modeling can then be used to develop risk maps outlining areas with elevated versus low projected risk of exposure to vectors, and infected vectors, within a given park based on associations with environmental factors for the specific vector collection locations (Eisen and Eisen 2008, 2011). This also could be augmented by convenience sampling: for example, encouraging visitors to submit ticks they find attached and feeding or still walking on their skin or clothing to park staff, or testing ticks that are found on road-killed animals and/or other wildlife trapped for research or management purposes for presence of human pathogens.

To conclude, mosquito- and tick-based surveillance for human pathogens is suitable for implementation in national parks and holds promise as the backbone of a nationwide surveillance program for mosquito- and tick-borne pathogens in the national park system. Flea vectors can be collected through the use of burrow swabs and tested for presence of *Y. pestis* but because of the low infection rates observed in host-seeking fleas even during active epizootics, it may be more practical to base plague surveillance efforts on surveys for animal die-offs, particularly rodents that can perish in large numbers during plague outbreaks, and testing of dead animals, or on serosurveys of carnivores that consume large numbers of potentially infected rodents (Gage et al. 1994, Gage 1999).

Human-Based Surveillance in National Parks

Human-based surveillance for exposure to vector-borne pathogens among national park visitors, who arrive from across the United States as well as from other countries, is challenging. This is because 1) visitors commonly will have left the park by the time symptoms occur and 2) public health investigators in the United States do not reliably collect detailed travel histories on patients diagnosed with notifiable tick- and mosquito-borne diseases (in contrast to plague), which makes it difficult to pin-point a national park as a potential or likely pathogen exposure location from patient case reports (D. Wong, unpublished data). Moreover, travel histories are more likely to be determined for patients residing outside of the endemic area for a given mosquito- or tick-borne pathogen compared with those residing within an endemic area where it can be reasonably assumed that exposure occurred near the home. Because of these limitations in travel history collection, assessing risk for mosquito- and tick-borne diseases in national parks using only human surveillance data would likely be a gross underestimate. Another consideration is that many national parks receive large numbers of international visitors. Even if the park visit is pin-pointed as a likely source of pathogen exposure when an afflicted person seeks care in the home country, this information may not be communicated to any public health agency in the United States. Finally, data for exposure of park staff to vector-borne pathogens should not be assumed to accurately reflect the risk for visitors, even when adjusted for time spent in the park, because staff and visitors may have very different vector contact rates resulting from specific behaviors or use of certain risk areas or microhabitats.

Another possible way of assessing exposure to vector-borne pathogens in national parks is to conduct active surveillance, for example, by visitors providing information as they leave the park regarding mosquito or tick bites and giving a blood sample for testing of exposure to pathogens. However, should this even be logistically feasible and approved by park managers, it may still prove difficult to distinguish exposures in the national park versus exposures having occurred in another endemic area just before arrival to the park. Because most of the samples would represent the earliest stage of infection, there also are other complicating issues including lack of detectable antibody response or circulating antigen. Based on these considerations, vector- or animal-based surveillance for pathogens is more feasible for the national parks compared with human-based surveillance, although both strategies would improve risk assessment estimates.

Fiscal Considerations for Surveillance of Vector-Borne Pathogens in National Parks

Surveillance of vector-borne pathogens in national parks is justified by the high visitation (hundreds of millions of annual visitors), our current lack of knowledge regarding the risk for staff and visitors of pathogen exposure within the parks, and the difficulty (unique to public lands) in assessing risk based on epidemiological data. Surveillance efforts would likely be conducted in collaboration between multiple federal agencies, including the National Park Service and the Centers for Disease Control and Prevention. We argue that an initial pilot effort, focusing on high use areas in 5–10 strategic parks with high visitor numbers and perceived presence of multiple vector-borne pathogens, would reveal the magnitude of the problem with vector-borne pathogens, particularly tick- and mosquito-borne pathogens, in U.S. national parks. The results would guide the decision of whether additional funds should be allocated to expand the effort to include a wider selection of parks and/or to institute routine surveillance in high risk parks.

Toward Improved Messaging to Promote Personal Protection Measures and Reduce Vector Bites in National Parks

The NPS preservation mission dictates that personal protection measures taken by staff and visitors must be the core strategy to reduce exposure to vector-borne pathogens in the national park system. This requires effective messages to promote personal protection measures and inform park visitors and staff of their responsibility for personal protection without discouraging outdoor activities by instilling fear disproportionate to the risk. The first steps to reduce exposure to vector-borne pathogens in a national park are to determine which vectors and vector-borne pathogens are present in that park, and then to assess when and where within the park exposure risk for a given pathogen occurs and reaches its peak. This knowledge provides the basis for effective messaging to park visitors, for example, by informing them that risk for exposure to ticks may occur from April–September, with a peak in late July–August, and that risk of encountering ticks is greatest along forest edges. In cases where risk of encountering ticks differs with geographic area within the park, tick exposure information could be presented together with a basic risk map depicting the areas where exposure risk is projected to be elevated versus low. The messaging also should provide guidance regarding 1) personal protective measures to prevent vector bites (http://www.cdc.gov/Features/StopTicks/; http://www.cdc.gov/Features/WestNileVirus/), 2) the importance of prompt and safe removal of attached ticks (some tick-borne pathogens, such as *B. burgdorferi*, are transmitted only after 1–3 d of attachment, which provides a window of opportunity to remove an infected tick before transmission occurs), and 3) which vector-borne pathogens occur in the park, what the early symptoms of infection are, and the importance of seeking medical care if symptoms arise. In the case of national parks where plague may occur, it also is important to clarify that infection can be acquired through handling of sick or dead animals. Studies are needed to determine the most effective messaging method(s) to make park visitors aware of the problem and what they can do to protect themselves, while still enjoying their visit to the park. Effective and multilingual messaging is important in national parks because they attract visitors from across the United States and other countries, many of which may not be familiar with the locally circulating vector-borne pathogens.

In exceptional situations, such as a major outbreak within a national park of a potentially severe vector-borne disease, risk reduction measures beyond personal protection may be considered. However, any such measures must be weighed against the NPS preservation mission and, should the need to suppress vectors be justified, management strategies must be tailored to the specific site to minimize the effect on nontarget invertebrates and vertebrates and ecological processes (National Park Service 2006).

We conclude that:

- The risk for exposure to vector-borne pathogens in U.S. national parks is poorly understood.
- This knowledge gap results from lack of a systematic surveillance program for vector-borne pathogens in U.S. national parks.
- Because of ecological and human behavioral differences, risk assessments (e.g., disease incidence or abundance of infected vectors) for neighboring areas outside of a national park cannot be assumed to be representative of risk within the park.
- Vector surveillance, complemented by risk modeling, may aid in identifying when and where within a certain park visitors and staff are at greatest risk for exposure to vectors and vector-borne pathogens.
- Improved knowledge of high risk areas and time periods facilitates the crafting of messages to inform park visitors and staff of the potential risk associated with vectors and vector-borne pathogens, and to inform them about their responsibility for personal protection measures.
- These considerations are not unique to U.S. national parks but rather apply broadly to public lands worldwide.

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Table 1

Key tick, mosquito, and flea vector species, and tick-, mosquito-, or flea-borne diseases, potentially occurring in U.S. national parks by National Park Service region

National Park Service region	Key vectors of pathogens to humans			Key diseases		
	Ticks[a]	Mosquitoes	Fleas	Tick-borne	Mosquito-borne	Flea-borne
Northeast and National Capitol	*Am. americanum*	*Aedes triseriatus*		Human babesiosis	Eastern equine encephalitis	
	Am. maculatum[b]	*Culex pipiens*		Human granulocytic anaplasmosis	La Crosse encephalitis	
	De. variabilis	*Culex salinarius*		Human monocytic ehrlichiosis	Saint Louis encephalitis	
	Ix. scapularis			Lyme disease	West Nile virus disease	
				Powassan virus disease		
				Rocky Mountain spotted fever		
				Rickettsia parkeri spotted fever		
				Tularemia		
Southeast	*Am. americanum*	*Aedes triseriatus*		Human monocytic ehrlichiosis	Eastern equine encephalitis	
	Am. maculatum	*Culex nigripalpis*		Lyme disease	La Crosse encephalitis	
	De. variabilis	*Culex quinquefasciatus*		Rocky Mountain spotted fever	Saint Louis encephalitis	
	Ix. scapularis	*Culex salinarius*		*Rickettsia parkeri* spotted fever	West Nile virus disease	
				Tularemia		
Midwest	*Am. americanum*[b]	*Aedes triseriatus*		Human babesiosis	Eastern equine encephalitis	
	De. variabilis	*Culex pipiens*		Human granulocytic anaplasmosis	La Crosse encephalitis	
	Ix. scapularis	*Culex quinquefasciatus*[b]		Human monocytic ehrlichiosis[b]	Saint Louis encephalitis	
		Culex salinarius		Lyme disease	West Nile virus disease	
		Culex tarsalis		Powassan virus disease	Western equine encephalitis	
				Rocky Mountain spotted fever		
				Tularemia		
Inter-mountain	*De. andersoni*	*Culex pipiens*[c]	*Eumolpianus eumolpi*	Colorado tick fever	Saint Louis encephalitis	Plague
	Or. hermsi	*Culex quinquefasciatus*[b]	*Oropsylla montana*	Relapsing fever	West Nile virus disease	
	Or. turicata	*Culex tarsalis*		Rocky Mountain spotted fever	Western equine encephalitis	
				Tularemia		
Pacific West	*De. andersoni*	*Culex pipiens*[c]	*Eumolpianus eumolpi*	Colorado tick fever	Saint Louis encephalitis	Plague

National Park Service region	Key vectors of pathogens to humans			Key diseases		
	Ticks[a]	Mosquitoes	Fleas	Tick-borne	Mosquito-borne	Flea-borne
	De. occidentalis	*Culex quinquefasciatus*[b]	*Oropsylla montana*	Human babesiosis	West Nile virus disease	
	De. variabilis	*Culex tarsalis*		Human granulocytic anaplasmosis	Western equine encephalitis	
	Ix. pacificus			Lyme disease		
	Or. hermsi			Relapsing fever		
	Or. turicata			Rocky Mountain spotted fever		
				Tularemia		

[a] Am., Amblyomma; De., Dermacentor; Ix., Ixodes; Or., Ornithodoros.

[b] Present in the southern part of this region.

[c] Present in the northern part of this region.