Potential Impacts of West Nile Virus on Wildlife in California

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Summary: This report was prepared by the UC Davis Wildlife Health Center at the request of the California Department of Fish and Game to serve as a resource regarding the potential effects of West Nile Virus (WNV) on California wildlife. WNV was first detected in southern California in 2003, and infection is expected to become widespread in 2004. Wildlife populations may be directly impacted if WNV infection results in mortality and reduced survival. In addition, wildlife may be positively or negatively affected by mosquito control activities (e.g., pesticides, wetland manipulation) aimed at protecting humans from WNV exposure. This paper presents a model for assessing and visualizing the potential impacts of WNV on wildlife in California, and provides recommendations for managing and monitoring these impacts.

WNV is transmitted and maintained in the environment primarily in a mosquito-bird cycle. California has a rich avifauna, and many bird species occur in areas that have a high to very high risk of WNV exposure. During the summer season when WNV vectors are most abundant, the greatest concentrations of bird species at risk occur in the Central Valley, coastal regions, and western Sierra Nevada Mountains. Some level of mortality due to WNV will occur in a substantial number of different species in these areas. For example, WNV has been identified in 492 dead birds (mostly crows) in southern California as of June 22, 2004. However, population-level impacts are most likely to occur among those bird species that have the smallest populations or very limited distributions. These rarer species are found in the same areas that have high species richness – primarily the Central Valley, coastal regions, western Sierra Nevada, and the Salton Sea and lower Colorado River areas. The geographic overlap of abundant and rare bird species creates a situation that may increase the threat of population-level impacts on rare species, since the presence of large numbers of birds and competent vectors increases the opportunity for virus amplification and transmission in these regions. In particular, locally dense populations of crows, as well as house sparrows and house finches, may raise the level of risk of infection for birds and other vertebrates (including people) in the same area.

The population-level impacts of WNV on amphibians, reptiles, and mammals are largely unknown. WNV exposure among these taxa will occur when they are fed upon by mosquitoes that have acquired WNV by feeding on birds. For reptiles and amphibians, this scenario is unlikely because the mosquito species that feed on reptiles and amphibians are relatively low in abundance and rarely feed on non-reptile or non-amphibian hosts. However, incidental exposure may occur upon predation and consumption of WNV-infected prey items, as can occur with birds. In general, the largest numbers of both abundant and rare species will be at risk for exposure in the Central Valley, coastal regions, Sierra Nevada Mountains, and the southeast region of California around the Salton Sea and Colorado River.

The options for managing WNV in California wildlife are limited. Mosquito control, the cornerstone of the public health response plan, may also be an important tool for managing WNV in wildlife. Wildlife managers should work with vector control personnel to identify and achieve common goals, maximize benefits for wildlife and people, and minimize negative outcomes. The public should be educated about WNV and wildlife (for information and links see www.wildlifehealthcenter.org). All segments of the population need to have access to good information whether it is hunters wondering about the safety of game, residents who find dead birds in their yards, or anyone wondering about the effects of vector control on wildlife. Disease surveillance and monitoring are key management actions, and they must be extended beyond collecting dead birds. Monitoring efforts should focus on estimating WNV exposure and mortality in bird populations (and other vertebrates) that are also being monitored for changes in abundance. Wherever possible, the effects of vector control on wildlife should be included in these monitoring efforts.

Introduction

Since the introduction of West Nile Virus (WNV) to the eastern United States in 1999 there has been considerable concern that this introduced mosquito-borne virus could have significant impacts on North American wildlife (Komar, 2003; Marra et al., 2004). However, it has been difficult to predict or evaluate the impacts of WNV on wildlife because we lack basic information on host susceptibility, viral pathogenicity, and vector competence across diverse geographic regions. Mortality attributed to WNV has been documented in an impressive and growing number of wildlife species (Marra et al., 2004), but for the most part this list of species does not provide meaningful insights into the demographic consequences of WNV in wildlife (also see www.audubon.org/bird/wnv/pdf/effects_on_wildlife.pdf).

This paper develops a model for predicting and assessing the direct and indirect impacts of WNV on wildlife in California. In particular, this model helps identify focal geographic areas of concern based on mosquito vector abundance and the occurrence of sensitive species. Although WNV may cause mortality across a wide range of species, our model emphasizes impacts at the population rather than individual animal level. Public health agencies are justifiably concerned about preventing any human fatalities due to WNV (CDC, 2003); however, the most significant impacts for wildlife would be those that threaten the persistence of entire populations or species. Thus, our model treats susceptible populations that have small numbers of animals or those with limited distributions (e.g., threatened or endangered species) as more vulnerable to WNV than more abundant or widespread species or populations.

Wildlife populations will be directly impacted by WNV if infection results in outright mortality and reduced survival. In addition, wildlife and people may be affected by vector control activities that are primarily aimed at protecting humans from WNV exposure (Their, 2001; Logomasini, 2004). There is considerable uncertainty as to whether control activities that reduce mosquito abundance (e.g., application of larvicides and adulticides, habitat manipulation) will have an overall positive or negative impact on wildlife. For example, reduced vector abundance may reduce the risk of WNV infection for wildlife and people, whereas the use of pesticides and habitat modification (e.g. changes in watering regimes) may, in and of themselves, adversely affect wildlife health and survival. In either case, the potential impacts of vector control will be more significant for small populations.

The primary goal of this paper is to provide a framework for predicting, assessing, and managing the effects of WNV on wildlife. Although the focus here is limited to WNV in California, the general approach can be used for predicting and assessing the impacts of infectious disease on wildlife regardless of the specific pathogen or geographic location. This approach (identifying focal areas and species or populations at risk) is useful for any situation where management decisions must be made based on very limited information.

Materials and Methods

We developed a model using ArcGIS to visualize risk factors for WNV exposure and assess the potential impacts of WNV on wildlife in California, expanding upon an approach presented by Van Riper et al. (2003). The major components of the model include the projected abundance of competent mosquito vectors, the richness (number) and distribution of avian species that could serve as sources of virus amplification, the richness and distribution of rare wildlife species belonging to four vertebrate classes (amphibians, reptiles, birds, mammals), and the projected areas where vector control activities will be implemented. Data sources are shown directly on GIS maps.

Vector Abundance

A competent mosquito vector is one that can retain and/or amplify a disease agent in its body and whose feeding habits focus on hosts that are susceptible to the disease agent. Over 50 mosquito species occur in California (Meyer and Durso, 1998), but only a few of these, in particular *Culex* spp., are considered competent and important as vectors for WNV among wildlife (Goddard et al., 2002). *Culex tarsalis*, a widespread species that feeds on both birds and mammals, is projected to be the most important vector species of WNV in suburban and rural California. Other species of interest include *Cx. stigmatosoma* that feeds preferentially on birds, and *Cx. erythrothorax* that is abundant in wetland habitats and feeds on both birds and mammals. *Culex pipiens pipiens* and *Cx. pipiens quinqefasciatus* also feed on birds and mammals, and they will be important vectors in urban areas in northern and southern California, respectively. Adult *Culex* mosquitoes lay eggs on the surface of standing (i.e., stagnant, not flowing) water. The resulting larvae and pupae undergo development within water until they emerge as winged adults and disperse to the surrounding areas.

Unfortunately, GIS maps of mosquito distribution and abundance are not yet available for California. Because mosquito abundance in any given area is directly dependent on the availability of suitable water sources, we used data on water availability to construct a predictive model of high, medium, and low WNV vector abundance. Data layers and sources included California Department of Water Resources Land Use Surveys (California Department of Water Resources, various contributors), Central Valley Vernal Pool Complexes (Robert F. Holland and CDFG, 1998), Central Valley Wetlands and Riparian GIS (CDFG and various cooperators, 1997), Multi-source Land Cover Data 2002 v1 (California Department of Forestry and Fire Protection, 2002), California Average Annual Precipitation in Inches, 1961-1990 (Oregon State University and CDFG, 1998), Federal Hydrologic Unit Codes in California and Vicinity, Version E (CDFG, 1996), Hydrography 1:100k (U.S. Geological Survey, CDFG, and Environmental Protection Agency, 1998), Lakes 1:100k (U.S. Geological Survey, CDFG, and State Water Resources Control Board, 1997), and DEM, 100 m resolution (U.S. Geological Survey, Defense Mapping Agency, CDFG, 2001).

Point values were assigned to data layers that included average annual precipitation, irrigated rice and pasture lands, water bodies, wetlands and riparian areas, stream density, and elevations < 1000 feet. This approach is most appropriate for vectors in suburban and rural areas (especially *C. tarsalis* which prefers lower elevations), and underestimates the abundance of mosquitoes (*Cx. p. pipiens* and *Cx. p. quinqefasciatus*) in urban areas that breed in underground storm drain systems, backyard sources, etc. The results were scaled into 13 levels separated by increments of 0.25, and values were then grouped into three categories of predicted vector abundance: 0–1.5 (low), 1.75–2.75 (medium), 3.0–4.5 (high).

Amplifying Hosts

The level of WNV transmission within a given area is strongly influenced by the availability of vertebrate amplifying hosts that serve as a source of virus for mosquito vectors. Good amplifying hosts are susceptible to infection, produce high levels of virus circulating in their blood (viremia), share habitat with vector mosquitoes, and survive long enough with the disease so that mosquitoes feed on them and transmit virus to other hosts. The following species were identified as some of the potential amplifying hosts in California: American crow, scrub jay, pinyon jay, gray jay, Stellar's jay, yellow-billed magpie, black-billed magpie, raven, house finch, house sparrow, and ring-billed gull (Komar, 2003). We created an amplifying host richness layer by combining distribution data (California Wildlife Habitat Relationships Species Distribution Maps, CDFG and California Interagency Wildlife Task Group, 2002) for each of these species with the predicted vector abundance GIS. Values were assigned to geographic areas in California based on the number of amplifying host species that occurred in that area. The assigned values per number of species were: 0 = 0 species, 0.25 = 1 to 2 species, 0.5 = 3 to 5 species, 0.75 = 6 to 8 species, 1.0 = 9 to 11 species. The amplifying host layer was then added to the vector abundance model to produce a predictive WNV risk model scaled into 11 levels, with the levels grouped into three categories of predicted risk levels: 0–0.5 (low), 0.75–1.75 (medium), 2.0–5.25 (high). This scale was further reduced to four classes for the WNV risk model (low = 0.5–1.0, medium = 1.25–2.0, high = 2.25–2.75, very high = 3.0–5.25) to facilitate analysis of risk relative to vertebrate species richness.

WNV Exposure and Wildlife Impacts

Although WNV has been shown to primarily affect birds, there is evidence indicating that other classes of vertebrates also may be susceptible (Komar, 2003; Marra et al., 2003, 2004). Utilizing existing databases (California Wildlife Habitat Relationships Species Distribution Maps, CDFG and California Interagency Wildlife Task Group, 2002) that are used by CDFG for wildlife conservation and management, we created species richness and rare species richness maps for amphibians (n = 50), reptiles (n = 79), birds (n = 367), and mammals (n = 179). These distribution maps are themselves predictive, in that they predict the distribution of vertebrate species based on habitat. Three levels of species richness (based on total number of species), and rare species richness (based on number of rare species) were identified and mapped for each group (amphibian, reptiles, birds, mammals). Rare species included those that are listed as threatened or endangered at the state or federal level (Table 1). Although these maps do not include all species within each vertebrate group, they do identify how wildlife diversity and rarity is apportioned within the state. Species richness maps were then integrated with the WNV risk map to identify the relationship between wildlife diversity (low, medium, high number of species) and the risk of exposure to WNV (low, medium, high, very high). Because small populations are at greater risk of extirpation than large populations, the maps of rare species richness and WNV risk portray not only the risk of exposure, but also the risk for serious demographic consequences.

Vector Control

Mosquito control activities are implemented by Mosquito and Vector Control Districts (MVCDs) in selected areas of California. Control efforts primarily involve the application of larvicides on bodies of standing water and management of water sources in an effort to reduce their ability to produce large numbers of mosquitoes. Aerial or ground applications of adulticides, which have a greater potential for impacting wildlife than larvicide treatments, are generally restricted to time periods and locations with high vector abundance levels or elevated risk for virus transmission to humans. Although the statewide mosquito response plan for WNV outlines different levels of vector control (Kramer, 2001), each MVCD functions with a significant degree of autonomy, and control activities are implemented on a case-by-case basis at the local level. Therefore, we identified areas where adulticide treatments would be applied by mapping the boundaries of MVCDs relative to 3 categories of human population density (urban > 4000, suburban 800–4000, and rural < 800 persons/sq mile within U.S. Census block groups).

Results

Vector Abundance and Risk of WNV Transmission

Mosquitoes are widely distributed in California, but vector abundance modeling predicted WNV vectors would be most abundant in the Central Valley, the Pacific Coast and coastal valley regions, and the Coachella and Imperial Valley regions (Figure 1). These results are most appropriate for *Cx. tarsalis*, a key vector in rural and suburban regions, since it prefers to breed in water found at low elevation (<1000 feet). An overall map of the risk of WNV in California was produced by combining predicted vector abundance and the distribution of avian amplifying hosts (Figure 2). The occurrence of suitable amplifying hosts in areas of predicted mosquito vector abundance emphasized that the risk of WNV transmission is highest in the Central Valley, the Pacific Coast and nearby inland regions, and areas around the Salton Sea and the lower Colorado River in southern California. The areas of least risk are the drier regions of the state, particularly the Mojave Desert region. The projected level of elevated vector abundance and WNV risk in the Death Valley region of the Mojave Desert is probably not accurate. The GIS data sources we used identify water drainages in this low elevation region. However, high levels of evapotranspiration (not incorporated in the model) limit available surface water in this region (as in most desert regions that are not irrigated) and reduce mosquito breeding opportunities.

WNV Risk and Species Richness

Risk of WNV exposure relative to species richness and rare species richness is shown for amphibians (Figures 3a, 3b), reptiles (Figures 4a, 4b), birds (Figures 5a, 5b) and mammals (Figures 6a, 6b). Birds, the primary host for WNV, are obviously at risk for WNV in much of the state. In general, the richness of amphibian (Figure 3a) and avian (Figure 5a) species largely mirror each other, and both mirror the risk of WNV throughout California. Thus, many of the areas with the largest number of amphibian and bird species tend to be areas at higher risk for WNV transmission. An explanation for this is that water plays an important role in determining where mosquitoes, amphibians, and birds occur. Mammal richness followed a pattern similar to birds and amphibians with the notable exception of the Central Valley, where WNV risk is high to very high, while the total number of mammal species is low relative to other regions in the state (Figure 6a). Reptile species richness tends to be highest in the drier regions of the state where vector abundance and WNV risk is low (Figure 4a); however, substantial numbers of reptile species do occur in coastal regions and the Sierra Nevada where WNV risk is high.

Rare species of birds (n = 27) are widely distributed across the state, with many of them occurring in areas of high to very high WNV risk (e.g., Central Valley, western Sierra Nevada Mountains, south coast region, Salton Sea and lower Colorado River region). Rare amphibian species (n = 10) are primarily distributed along the coastal regions and in the Sierra Nevada Mountains. Rare mammal species (n = 21) are most heavily concentrated in the Mojave Desert region and the lower Central Valley. Rare reptile species (n = 10) are concentrated in the Sierra Nevada Mountains, the Central Valley, coastal regions and the northern portion of the state. A composite view of species rarity and WNV risk illustrates that the risk of demographic impacts across vertebrate taxa is greatest in the Central Valley and selected coastal regions (Figure 7). However, many rare species may only occupy a limited portion of their range at any given time, so areas with even moderate risk of WNV exposure may be important.

Vector Control

Figure 8 shows that MVCDs are primarily located in the Central Valley, the central Pacific Coast regions, and southern California where the human population density is high. Not surprisingly, the areas under MVCD jurisdiction largely correspond to those areas with the highest predicted vector abundance and predicted WNV risk (Figures 1 and 2). While mosquito control activities will be implemented in regions of high vector abundance and high human population density, they also will overlap into areas with high levels of rare species richness (Figure 8). Thus, vector control will be implemented in areas harboring large numbers of rare animal species.

Discussion

Evaluating and mitigating the impact of WNV on California wildlife requires that we assess the risk of exposure, the consequences of infection, and the effects of vector control efforts. Because site-specific knowledge and financial resources are limited, it is essential that research and management efforts be prioritized based upon the best available biological knowledge. The model developed in this paper, coupled with knowledge gained in other states since the introduction of WNV in 1999, was used to develop the following view of WNV risk and impacts for California wildlife. However, it is important to recognize that predictive models based on limited data have inherent weaknesses, and the results or predictions presented here should be viewed as preliminary.

WNV Transmission and Wildlife Exposure Risk

WNV is transmitted and maintained in the environment primarily in a mosquito-avian cycle, and *Culex* species are considered to be the most important vectors of WNV for California wildlife species (Goddard et al., 2002). The importance of any given mosquito species in transmitting WNV depends on its ability to acquire and transmit the virus to new hosts (vector competence), its host feeding preferences (birds, mammals, etc.), and its distribution and abundance. The propensity of *Cx. tarsalis* to feed on both birds and mammals indicates that it will transmit the virus among avian hosts, as well as from birds to mammals. *Culex p. pipiens* (northern California) and *Cx. p. quinquefasciatus* (southern California) transmit WNV less efficiently than *Cx. tarsalis*, but they will play an important role in transmitting WNV in wildlife near urban areas since they are common, widespread, and feed on both birds and mammals. Other important species include *Cx. stigmatosoma* that feeds preferentially on birds, and *Cx. erythrothorax* that is abundant in wetland habitats and feeds on both birds and mammals. The extent to which *Culex* species feed on reptiles and amphibians in California is poorly understood, but WNV transmission from birds to amphibians and reptiles is a possibility.

Water sources that support the production of important WNV vectors were emphasized in the vector abundance model (Figure 1). The predicted abundance of vectors is remarkably high in the northern two-thirds of the Central Valley due to the heavy concentration of irrigated agricultural land and wetlands. However, suitable mosquito habitat is present throughout many other regions of California, including the coastal and inland valley areas, the Sierra Nevada, and the region surrounding the Salton Sea and Lower Colorado River. The ability of *Cx. p. pipiens* and *Cx. p. quinquefasciatus* to flourish in urban and suburban settings further expands the predicted distribution of competent vectors in the state.

The risk of WNV transmission occurring in any given area also depends on the makeup of the avian community. Once infected from a bite from a WNV-carrying mosquito, birds that are considered to be competent hosts amplify the virus in their blood and tissues in sufficient quantity, and for sufficient duration, to serve as a source of infection for mosquitoes. Corvids (crows, jays, and magpies), house sparrows, house finches, and ring-billed gulls were found to be the most competent avian hosts for WNV among 25 bird species evaluated in an experimental trial, and they are likely to be important reservoirs of WNV in urban and suburban environments (Komar et al., 2003). Many of these species are locally abundant, colonial or semi-colonial, flocking species that are prevalent where human foods (crops, garbage, handouts) are abundant and dependable. American kestrels, great horned owls, and killdeer were also found to be competent hosts in the same experimental trial, and there may be many more unrecognized avian species that can effectively amplify WNV once infected.

Differences in the abundance of birds that serve as amplifying hosts for WNV will influence the risk of WNV exposure for wildlife and people. For example, American crows congregate in large numbers at roosting sites during the evening when *Culex* mosquitoes are most active. These roost sites may serve as “hot spots” for virus amplification and transmission. The occurrence of locally abundant crow populations may help explain why bird mortality has been high in east Los Angeles, southwest San Bernardino, and western Riverside counties in 2004, even though our model predicted a relatively low risk for these areas (http://westnile.ca.gov/maps.htm; Figure 2). Alternatively, the relative abundance of potential amplifying hosts such as house sparrows and house finches may be more important than the abundance of corvids, at least in some areas. Although our model does not incorporate abundance data, Breeding Bird Survey and Christmas Bird Count data for birds in California are available at http://www.mbr-pwrc.usgs.gov/bbs and www.audubon.org/bird/cbc/hr/index.html.

WNV infection in humans and most other non-avian vertebrates is tangential to the primary avian amplification cycle in that these species generally are not able to infect mosquitoes; therefore, the cycle reaches a dead-end. However, this generalization is not all inclusive and some species of mammals, reptiles, and amphibians may develop sufficient viremias in their blood to possibly serve as competent hosts for WNV transmission. To date, several species of rodents, lemurs, as well as American alligators have been shown to produce viremias adequate to be infectious to mosquitoes (Kramer and Bernard, 2001; Xiao et al., 2001; Komar, 2003; Miller et al., 2003). Conversely, in an experimental trial, the green iguana, Florida garter snake, and American bullfrog were shown to be poor amplifying hosts for WNV (Klenk and Komar, 2003).

The model of WNV exposure risk (Figure 2) shows that there are extensive portions of California with the potential for WNV transmission within or among bird species, or from birds to mammals (and perhaps reptiles and amphibians) (Figures 3 to 6). In addition to transmission through mosquito bites, alternative bird-to-bird transmission routes, including direct contact and oral transmission, and possibly transovarial transmission (from parent to offspring), have been documented (McLean et al., 2001; Komar, 2003). Both oral and cloacal shedding of WNV viral particles have been detected in the majority of birds evaluated (Komar, 2003). The possibility of oral transmission, or infection from ingesting infected prey, may have important implications for raptors, carrion-feeders, and mosquito-feeding avian species, such as swifts, swallows, and flycatchers (Marra et al., 2003). Migration of infected avian hosts may also play a role in distribution and spread of WNV, but infection in actively migrating birds has not yet been documented in North America (Komar, 2003; Marra et al., 2003; Owen et al., 2003).

Potential Consequences of WNV in California Wildlife

The impact of WNV on free-ranging wildlife populations since its introduction to North America is largely unknown (see http://www.audubon.org/bird/wnv/pdf/effects_on_wildlife.pdf). While the health care delivery system for humans and domestic animals ensures adequate monitoring for these species, surveillance efforts in wildlife have focused mostly on urban and peri-urban bird species that are able to provide an early warning for impending exposure in humans. To date in North America, WNV infection is known to cause death in over 200 species of native and exotic birds and 20 species of mammals (Komar, 2003), and this list continues to grow (Marra et al., 2003, 2004). Experimental WNV infection caused death mainly in passerines (corvids, house sparrows, common grackles) and ring-billed gulls, but morbidity and mortality were also seen in species from the orders Anseriformes, Falconiformes, Galliformes, Gruiformes and Columbiformes, Psittaciformes, Strigiformes, and Piciformes.

Among the avian species that have been evaluated in the limited trials to date, corvids are thought to be one of the most vulnerable to mortality from WNV infection. Crows experienced 100% mortality when experimentally infected with WNV (Komar et al., 2003), and higher rates of WNV infection have been reported in crows than in other species in dead bird surveillance programs (CDC, unpublished data). Crows in California will experience considerable mortality from WNV. Disappearance or death in nearly 40% of marked American crows nesting in Oklahoma (Caffrey et al., 2003) and 33% of marked crows in central New York (McGowan and Clark, 2003) coincided with the appearance of WNV in these regions. The predominance of crows among all birds reported in WNV dead bird surveillance programs may be influenced by monitoring efforts that rely on the public and vector control staff to report and submit carcasses (Marra et al., 2003). Crows are common in urban environments and are highly visible to the public. In addition to crows, mortality events attributed to WNV have also been described in blue jays, black-billed magpies, northern cardinals, common grackles, house finches, house sparrows, great-horned owls, red-tailed hawks, sharp-shinned hawks, barred owls, double-crested cormorants and American white pelicans in 2002 and 2003 (USGS National Wildlife Health Center, Quarterly Mortality Reports, http://www.nwhc.usgs.gov/pub_metadata/qrt_mortality_report.html).

California has a rich avifauna, and many bird species occur in areas that will have high to very high risk of WNV exposure (Figure 5). During the summer season when WNV vectors are most abundant, the greatest concentrations of bird species at risk occur in the Central Valley, coastal region, and western Sierra Nevada Mountains. Some level of mortality due to WNV will occur in a substantial number of different species in these areas. However, population-level impacts will occur among those bird species that have the smallest populations or very limited distributions. Figure 5b reveals that these rarer species are found in the same areas that have the highest species richness – primarily the Central Valley, coastal regions, western Sierra Nevada, and the Salton Sea and lower Colorado River areas. Unfortunately, the geographic overlap of abundant and rare bird species creates a situation that may increase the threat of population-level impacts on rare species, since the presence of large numbers of birds and competent vectors increases the opportunity for virus amplification and transmission in these regions. For example, locally dense populations of crows may raise the level of risk of infection for other less common birds in the same area.

It is important to recognize that WNV may have substantial impacts on populations or species that are relatively abundant but have a limited distribution. For example, yellow-billed magpies are relatively abundant and are not listed as threatened or endangered. However, their distribution is limited to areas that have a very high risk for WNV transmission, and they may be subject to high levels of mortality since they belong to the corvid family. The same considerations hold true for the Island scrub-jay (also called Santa Cruz jay), a corvid which is endemic and limited to the island of Santa Cruz in the Channel Islands.

The population-level impacts of WNV on amphibians, reptiles, and mammals (non-domestic) are largely unknown. WNV exposure among these taxa will occur when they are fed upon by mosquitoes that have acquired WNV by feeding on birds. For reptiles and amphibians, this scenario seems unlikely because the mosquito species that feed on reptiles and amphibians are relatively low in abundance and rarely feed on non-reptile or non-amphibian hosts (Meyer and Durso, 1998). However, it has been speculated that incidental exposure may occur upon predation and consumption of WNV infected prey items. In general, the largest number of both abundant and rare (Figures 3, 4, 6) species will be at risk for exposure in the Central Valley, coastal regions, Sierra Nevada Mountains, and the southeast region of California around the Salton Sea and Colorado River. A composite view of WNV and rare species richness (for all 4 vertebrate groups) reinforces the conclusion that these geographic regions are focal areas of risk (Figure 7).

Impacts of Vector Control on Wildlife

In addition to the direct impacts of WNV, California wildlife may be indirectly affected, positively or negatively, by vector control efforts aimed at protecting human health. Vector control activities are conducted at the local level by MVCDs based on an Integrated Pest Management (IPM) strategy. This approach utilizes knowledge of mosquito biology and effective control measures (pesticides, habitat management, etc.) in such a way as to minimize the risk to people and the environment, including wildlife. Legislation passed in May 2004 (California Assembly Bill 1454) requires that vector control be conducted in cooperation or consultation with the California Department of Health Services to ensure that activities are performed by licensed professionals employing appropriate methods and materials. Summary information regarding human exposure to pesticides used in mosquito control is available from the Center for Disease Control (www.cdc.gov/mmwr/preview/mmwrhtml/mm5227a1.htm).

The impacts of WNV on California wildlife will not occur in isolation from vector control activities. In fact, it is clear that the areas covered and targeted by the MVCD are the same areas where wildlife is at risk (Figure 8). Vector control activities that may affect wildlife include the application of mosquito larvicides and adulticides, the manipulation of water sources to reduce their potential for producing mosquitoes, and the introduction of non-native mosquitofish (*Gambusia affinis*). These activities could negatively impact some wildlife species or populations if they cause mortality, reduce food supplies, or affect habitat availability or suitability. Conversely, vector control activities may benefit some wildlife species or populations by reducing WNV transmission within and among wildlife populations.

The California Department of Health Services has developed a 3-tiered response plan that calls for increasing levels of vector control as the threat of WNV transmission to humans increases (Kramer, 2001). During a normal mosquito season when there is no evidence of active virus transmission (Level 1), larvicidal compounds are typically applied to standing bodies of water when surveillance indicates that mosquito larvae and pupae have reached some predetermined threshold. Larvicides used in California include *Bacillus thuringiensis israelensis*, methoprene (an insect growth regulator), larvicidal oils, monomolecular surface films, and diflubenzuron (chitin synthesis inhibitor). Although there is some controversy about effects on nontarget species, larvicidal compounds are expected to have minimal direct or indirect impact on wildlife (Their, 2001; Logomasini, 2004). For example, diflubenzuron is considered to be practically nontoxic to birds, fish, aquatic invertebrates and honey bees (http://extoxnet.orst.edu/pips/difluben.htm). Detailed information on adulticides and larvicides is available at http://npic.orst.edu/wnv/pesticideinfo.htm#mosqmanage, and pesticide use information for California is available at www.cdpr.ca.gov/docs/westnile/.

Adulticides are currently used for vector control in California on a limited basis, and the use of adulticides will be increased if the WNV response is elevated to Level 2 (Emergency Planning Conditions) or Level 3 (Epidemic Conditions). Adulticides that may be used in California include organophosphates (malathion, naled) and pyrethrins (permethrin, resmethrin, sumithrin) (Kramer, 2001). Adulticides pose a greater threat to wildlife since they are more toxic to both target and non-target species than larvicides (Their, 2001; Logomasini, 2004). Adulticides may be applied in urban or suburban areas to target mosquitoes near people, or they may be applied near wetlands to reduce adult mosquito populations at their source (Figure 8). While adulticides will probably be used only within established vector control districts during Level 2, they may be used anywhere they are needed during epidemic transmission of WNV (Kramer, 2001). Larvicides are used most effectively early in the mosquito season before large numbers of adult mosquitoes are present. In contrast, adulticide use will increase once WNV transmission to people is actively occurring and when there is an immediate need to reduce mosquito numbers. This situation is already occurring in San Bernardino County in southern California as of June 24, 2004.

Mosquito control can also be accomplished by managing wetland habitats to reduce mosquito production (Batzer and Resh, 1992; Smith et al., 1995). The duration and timing of flooding (i.e., delayed fall flooding, rapid fall flooding, rapid flooding and draining) of wetlands can significantly influence mosquito production (Kwasny et al., 2004). Likewise, vegetation management such as mowing, burning , disking, haying, and selective grazing can decrease mosquito breeding habitat in managed wetlands. However, each of these activities has the potential to negatively alter the wetland environment in terms of wildlife suitability and use. A promising approach currently being pursued by CDFG to minimize negative impacts on wildlife is the development of Best Management Practices (BMPs) for reducing mosquitoes in managed wetlands (e.g., Kwasny et al., 2004). The BMPs will vary by locale, and it is important that wetland managers continue to consult with their local MVCD to identify which BMPs can be effectively implemented.

Recommendations for Managing and Monitoring WNV in Wildlife in California

The model presented in this paper helps identify focal geographic areas of concern based on predicted vector abundance and the occurrence of sensitive species. It was developed because we lack key data on the ecology of WNV in California. The management and monitoring strategies outlined below should be adaptively modified as WNV emerges across the state and we gain the knowledge needed to better identify areas and species at risk.

Management Recommendations

The options for managing WNV in California wildlife are limited. Wildlife (especially birds) and people in over two-thirds of California are at risk of WNV exposure (Figure 2), but the few preventive measures that are available are primarily useful for people or domestic animals. For example, the "Fight the Bite" campaign encourages people to prevent infection by avoiding mosquito bites (repellants, protective clothing, awareness of peak mosquito hours), making homes mosquito-proof (drain standing water, fix window screens), and helping communities control the disease (report dead birds, support mosquito control efforts, public education) (http://www.cdc.gov/ncidod/dvbid/westnile/resources/FighttheBite_prevention.pdf).

Mosquito control, the cornerstone of the public health response plan, may also be an important tool for managing WNV in wildlife. Wildlife managers should carefully consider the potential benefits for wildlife of reducing mosquito numbers, and they should work with the MVCDs throughout California to identify and achieve common goals, maximize benefits for wildlife and people, and minimize negative outcomes (Figure 8; http://mvcac.org/agencies.htm). Since many vector control activities will take place in and around wetlands, it is particularly important for wetland managers to initiate a dialogue and establish a working relationship with local vector control personnel. Wherever possible, monitoring efforts should be conducted in association with control efforts to identify positive and negative effects of vector control on wildlife.

Although no vaccine is available for humans, vaccines have been developed and are recommended for use in horses because up to 30% of WNV-infected horses may die (http://www.vetmed.ucdavis.edu/ceh/wnv_info.html).
These vaccines are being evaluated in captive wildlife at zoos and rehabilitation centers (http://www.projectwildlife.org/news.winter2002.newscastle.htm), but their effectiveness is unproven. In general, vaccination is not a viable option for free-ranging wildlife (especially birds) because of cost and logistical issues. However, vaccination may be appropriate for selected free-ranging wildlife species that are intensively managed, as is underway for the California condor (http://www.nature.nps.gov/biology/wildlifehealth/wnv.htm).

Disease surveillance and monitoring are key management actions. Many states, including California, have developed cooperative response plans for WNV with participation from their state wildlife agency (some of these are listed at http://npic.orst.edu/wnv/statelinks.htm). However, in most states it appears that WNV surveillance in wildlife is limited to collecting and testing selected species of dead birds (corvids and raptors). Unfortunately, this limited approach provides little insight into the population-level effects of WNV on wildlife. This is one reason why the effects of WNV on wildlife are still largely unknown four years after its emergence in the United States. California has the opportunity to develop and implement a thoughtful surveillance and monitoring strategy for wildlife, and detailed recommendations are provided below.

The California Department of Fish and Game, as well as other organizations, should take an active role in educating the public about WNV in wildlife. All segments of the population need to have access to good information whether it is hunters wondering about the safety of game, residents who find dead birds in their yards, or anyone wondering about the effects of vector control on wildlife. Websites with fact sheets, answers to frequently asked questions, and links to other key organizations are essential, as are lay publications and media presentations (see www.wildlifehealthcenter.org). The California Department of Health Services hosts an excellent website on WNV that provides some information on wildlife (http://westnile.ca.gov/), as does the Center for Disease Control (http://www.cdc.gov/ncidod/dvbid/westnile/).

Monitoring Recommendations

Birds should receive the highest priority for monitoring since they are the primary hosts for WNV, but many of the comments below also apply to amphibians, reptiles and mammals. The choice of what species to monitor should be based on several factors including their abundance, their distribution relative to WNV risk, their susceptibility to WNV, and whether it is logistically feasible and cost-effective to monitor adequate numbers. The highest predicted risk areas include the Central Valley, coastal regions, western Sierra Nevada, the Salton Sea, and lower Colorado River area. The presence or absence of vector control activities in these areas also should be incorporated into the study design to determine whether or not these activities have a positive, negative, or mixed effect on the wildlife species in question.

Potential candidate species include those rare species in Table 1 that occur in these high risk areas, as well as more abundant species that may have a limited distribution or be particularly susceptible to WNV. The 11 potential amplifying hosts used in our model would also be good candidates for evaluating WNV exposure in various regions in the state. Consideration should be given to monitoring at least one species from each of the following groups (this includes some of the amplifying hosts): corvids (crows, yellow-billed magpies, scrub jays), raptors (Swainson's hawk, great gray owl, Peregrine falcon), peri-urban passerines (house sparrow, house finch), and coastal species (ring-billed gulls, brown pelican). Species that are already the focus of ongoing demographic studies (often for reasons other than WNV) may provide better opportunities for monitoring than species for which there is no preexisting research infrastructure (i.e., established methods and trained personnel) or baseline data.

To understand the impacts of WNV on California wildlife, monitoring efforts should focus on estimating WNV-exposure levels and WNV-specific mortality in populations that are also being monitored for changes in abundance. Exposure to WNV can be estimated by sampling populations to determine the prevalence of virus or antibodies to the virus. However, sampling live animals in the field for WNV is not trivial and requires appropriate training, expertise, and handling permits. Furthermore, the prevalence of virus or antibody in a population is not very meaningful unless it is accompanied by an estimate of how exposure affects survival and population size.

To estimate cause-specific mortality, individuals within a population must be marked and closely monitored, and individuals that die must be examined and sampled to identify the cause of death. Radiotelemetry provides a useful approach for estimating cause-specific mortality in free-ranging populations. Under good conditions with intensive radiotracking efforts, radiotelemetry will also facilitate retrieval of dead individuals. This technique is most practical for large-bodied species with limited geographic range. If populations cannot be marked, daily surveys of small areas with known or countable subpopulations (nest sites, rookeries) could be used to identify and retrieve carcasses. However, carcass recovery rates are typically very low for nontelemetered animals and this approach introduces many biases associated with animal size, cover, etc. All carcasses that are recovered must be handled properly to obtain useful cause-specific mortality data. Field personnel must recover and ship dead animals (chilled on ice) within 24-48 hours of death to an appropriate diagnostic laboratory where arrangements for testing have been established in advance. To report dead birds in California call 1-877-WNV-BIRD or report them online at www.westnile.ca.gov. Guidelines for biologists handling birds are available at www.nwhc.usgs.gov/research/west_nile/wnv_guidelines.html.

A key component of WNV monitoring is linking exposure and mortality to changes in population abundance. This means that populations must be monitored for changes in abundance, or at a minimum, that survival rates be calculated. There are many ways to track survivorship and population trends, but without cause-specific mortality information it will not be possible to establish a causal relationship between WNV exposure and changes in survival rates or abundance. Again, radiotelemetry will be useful for some but not all species.

Since only a few species can be intensively monitored, other data sets may be used to gain some level of insight in the potential effects of WNV. For example, North American Breeding Bird Survey and Christmas Bird Count data may be useful to identify gross changes in abundance before, during and after the introduction of WNV in California. This approach will indicate whether the introduction of WNV is associated with demographic changes, but it will not establish causality. The North American Breeding Bird Survey revealed local declines in avian species associated with the occurrence of WNV activity in the eastern United States in 2000–2001 (Sauer and Marra, 2003). Likewise, Christmas Bird Count Data from 1989–2002 was used to evaluate changes in counts in 10 northeastern bird species (American crows, great horned owls, red-tailed hawks, downy woodpeckers, chickadees, white-breasted nuthatch, blue jays, northern mockingbirds, house sparrows, and northern cardinals) before and after the arrival of WNV (Caffrey and Peterson, 2003). A substantial and sustained decline was noted only for American crows from 1999–2002, while counts for other species were either stable or were difficult to interpret in light of previous population fluctuations.

Sampling bias is inherent in nearly all survey work and will vary according to the species and geographic area being monitored. The dead bird surveillance programs for WNV are intentionally biased towards selected species such as crows that succumb from infection and occur near urban areas because dead crows provide an early warning of potential human exposure (Kramer, 2001). The California dead bird surveillance program does provide useful information (http://westnile.ca.gov/), but inferences cannot be directly extrapolated to other species or other geographic regions. Sampling bias will be an issue for any species that is monitored, and when sampling biases can not be addressed through study design, factors contributing to bias should be measured during monitoring to permit adjustment for bias in the analysis phase.

WNV surveillance in wildlife is relatively expensive and labor intensive. A reasonable approach is to initiate a collaborative monitoring strategy that shares resources to the maximal extent possible. To reduce cost and effort, WNV monitoring efforts should focus on populations at risk that are already being intensively monitored with radiotelemetry or another sensitive measure of survival. Monitoring for WNV may be added to these studies with minimal expense, and long-term ongoing studies offer the greatest potential for identifying meaningful changes over time. The CDFG Resource Assessment Program is working with the UC Davis Wildlife Health Center and others to develop an implementation plan that prioritizes projects that address key monitoring needs.

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Literature Cited

Batzer DP and VH Resh. 1992. Wetland management strategies that enhance waterfowl habitat can also control mosquitoes. *Journal of the Mosquito Control Association*. 8:117-125.

Caffrey C, TW Weston, and S Smith. 2003. High mortality among marked crows subsequent to the arrival of West Nile virus. *Wildlife Society Bulletin*. 31:870-872.

Caffrey C and C Petersen. 2003. Christmas Bird Count data suggest West Nile virus may not be a conservation issue in the northeastern United States. *American Birds* .The 103rd Christmas Bird Count:14-21.

Center for Disease Control. 2003. http://www.cdc.gov/ncidod/dvbid/westnile/resources/wnv-guidelines-aug-2003.pdf

Goddard LB, AE Roth, WK Reisen, and TW Scott. 2002. Vector competence of California mosquitoes for West Nile virus. *Emerging Infectious Diseases*. 8:1385-1391.

Klenk K and N Komar. 2003. Poor replication of West Nile virus (New York 1999 strain) in three reptilian and one amphibian species. *Am J Trop Med Hyg*. 69:260-262.

Komar N. 2003. West Nile virus: epidemiology and ecology in North America. *Adv Virus Res*. 61:185-234.

Komar N, S Langevin, S Hinten, N Nemeth, E Edwards, D Hettler, B Davis, R Bowen, and M Bunning. 2003. Experimental infection of North American birds with the New York 1999 strain of West Nile virus. *Emerg Infect Dis*. 9:311-322.

Kramer LD and KA Bernard. 2001. West Nile virus infection in birds and mammals. *Ann N Y Acad Sci*. 951:84-93.

Kramer VL. 2001. California state mosquito-borne virus surveillance and response plan. California Department of Health Services.

Kwasny DC, M Wolder, and CR Isola. 2004. Best management practices for mosquitoes in managed wetlands. 39 pp. (unpublished report).

Logomasini A. 2004. Pesticides and the West Nile virus: an examination of environmentalist claims. Competitive Enterprise Institute. 31 pp.

Marra PP, SM Griffing, and RG McLean. 2003. West Nile virus and wildlife health. *Emerg Infect Dis*. 9:898-899.

Marra PP, S Griffing, C Caffrey, AM Kilpatrick, R McLean, C Brand, E Saito, AP Dupuis, L Kramer, and R Novak. 2004. West Nile virus and wildlife. *Bioscience*. 54:393-402.

McGowan K and A Clark. 2003. The impact of West Nile virus on a population of American crows in central New York. West Nile Virus and Wildlife Health Workshop 2003.

McLean RG, SR Ubico, DE Docherty, WR Hansen, L Sileo, and TS McNamara. 2001. West Nile virus transmission and ecology in birds. *Ann N Y Acad Sci*. 951:54-57.

Meyer RP and SL Durso. 1998. Identification of the mosquitoes of California. Mosquito and Vector Control Association of California, Sacramento, CA.

Miller DL, MJ Mauel, C Baldwin, G Burtle, D Ingram, ME Hines, II, and KS Frazier. 2003.West Nile virus in farmed alligators. *Emerg Infect Dis*. 9:794-799.

Owen J, F Moore, and N Komar. 2003. Migrating birds as potential West Nile virus dispersal vectors. West Nile Virus and Wildlife Health Workshop 2003.

Sauer J and P Marra. 2003. Using the North American Breeding Bird Survey to document the consequences of West Nile virus on bird populations. West Nile Virus and Wildlife Health Workshop 2003.

Smith WD, GL Rollins, and RL Shinn. 1995. A guide to wetland habitat management in the Central Valley. California Department of Fish and Game. 34 pp.

Their A. 2001. Balancing the risks: vector control and pesticide use in response to emerging illness. *Journal of Urban Health*. 78: 372-381.

Van Riper III C, RM Stevens, LJ McGrath, C Obrien, and KL Ecton. 2003. Habitat partitioning by neotropical migrant warblers along the lower Colorado River corridor and potential influences on West Nile Virus transmission. http://charlesvanriper.com/wnv/west_nile_virus.htm

Xiao SY, H Guzman, H Zhang, AP Travassos da Rosa, and RB Tesh. 2001. West Nile virus infection in the golden hamster (*Mesocricetus auratus*): a model for West Nile encephalitis. *Emerg Infect Dis*. 7:714-721.

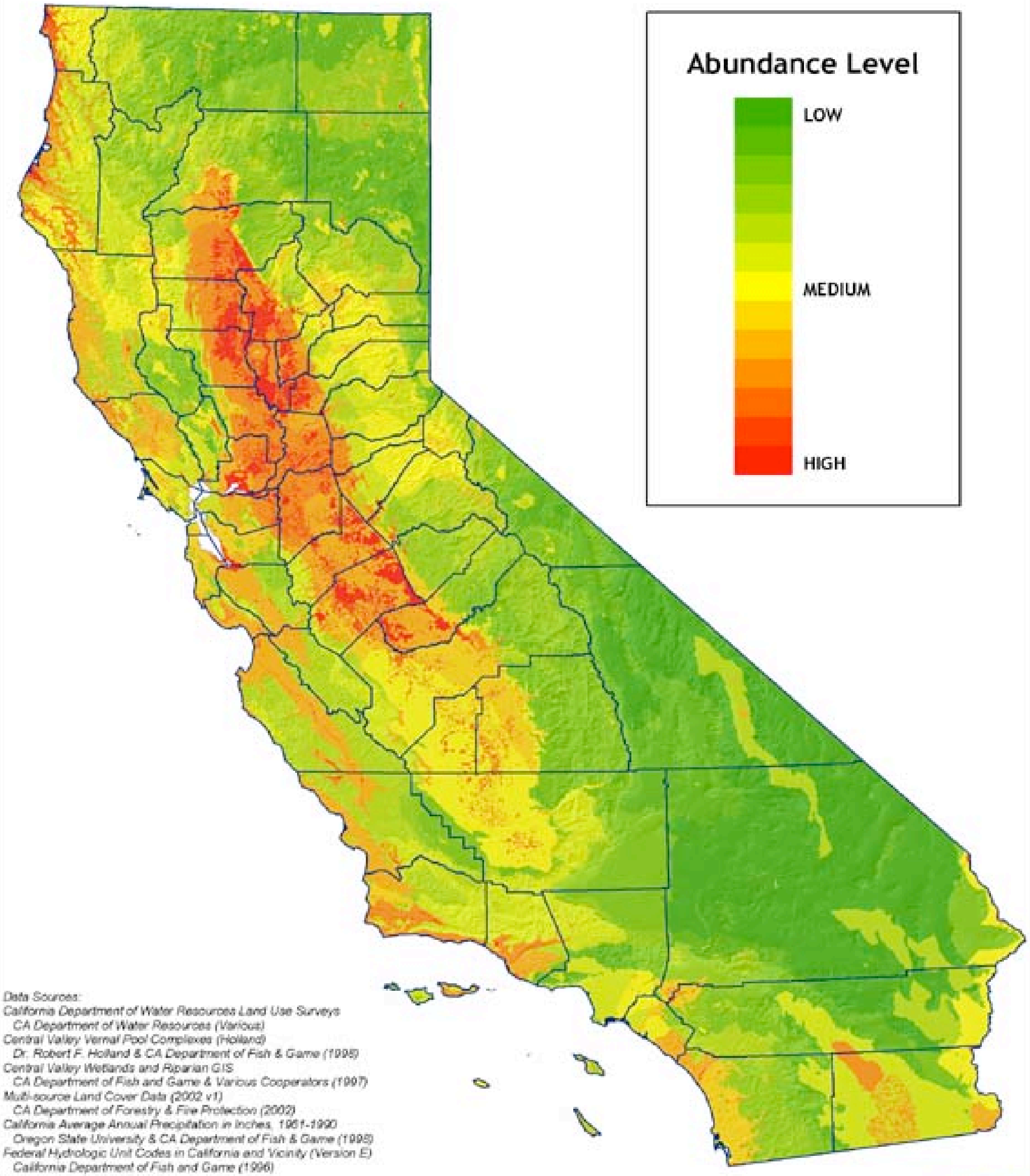
TABLE 1. RARE SPECIES USED IN GIS ANALYSES.

	AMPHIBIANS	SPECIES
1	LONG-TOED SALAMANDER	*Ambystoma macrodactylum*
2	SISKIYOU MOUNTAINS SALAMANDER	*Plethodon stormi*
3	DESERT SLENDER SALAMANDER	*Batrachoseps aridus*
4	KERN CANYON SLENDER SALAMANDER	*Batrachoseps simatus*
5	TEHACHAPI SLENDER SALAMANDER	*Batrachoseps stebbinsi*
6	SHASTA SALAMANDER	*Hydromantes shastae*
7	LIMESTONE SALAMANDER	*Hydromantes brunus*
8	BLACK TOAD	*Bufo exsul*
9	SOUTHWESTERN TOAD	*Bufo microscaphus*
10	RED-LEGGED FROG	*Rana aurora*
	BIRDS	
1	BROWN PELICAN	*Pelecanus occidentalis*
2	CALIFORNIA CONDOR	*Gymnogyps californianus*
3	BALD EAGLE	*Haliaeetus leucocephalus*
4	SWAINSON'S HAWK	*Buteo swainsoni*
5	PEREGRINE FALCON	*Falco peregrinus*
6	BLACK RAIL	*Laterallus jamaicensis*
7	CLAPPER RAIL	*Rallus longirostris*
8	SANDHILL CRANE	*Grus canadensis*
9	SNOWY PLOVER	*Charadrius alexandrinus*
10	LEAST TERN	*Sterna antillarum*
11	MARBLED MURRELET	*Brachyramphus marmoratus*
12	YELLOW-BILLED CUCKOO	*Coccyzus americanus*
13	ELF OWL	*Micrathene whitneyi*
14	SPOTTED OWL	*Strix occidentalis*
15	GREAT GRAY OWL	*Strix nebulosa*
16	GILA WOODPECKER	*Melanerpes uropygialis*
17	NORTHERN FLICKER	*Colaptes auratus*
18	WILLOW FLYCATCHER	*Empidonax traillii*
19	BANK SWALLOW	*Riparia riparia*
20	CALIFORNIA THRASHER	*Toxostoma redivivum*
21	LOGGERHEAD SHRIKE	*Lanius ludovicianus*
22	BELL'S VIREO	*Vireo bellii*
23	CALIFORNIA TOWHEE	*Pipilo crissalis*
24	SAGE SPARROW	*Amphispiza belli*
25	SAVANNAH SPARROW	*Passerculus sandwichensis*
26	GILDED FLICKER	*Colaptes chrysoides*
27	CALIFORNIA GNATCATCHER	*Polioptila californica*

	MAMMALS	
1	BRUSH RABBIT	*Sylvilagus bachmani*
2	MOUNTAIN BEAVER	*Aplodontia rufa*
3	SAN JOAQUIN ANTELOPE SQUIRREL	*Ammospermophilus nelsoni*
4	MOHAVE GROUND SQUIRREL	*Spermophilus mohavensis*
5	LITTLE POCKET MOUSE	*Perognathus longimembris*
6	HEERMANN'S KANGAROO RAT	*Dipodomys heermanni*
7	GIANT KANGAROO RAT	*Dipodomys ingens*
8	STEPHENS' KANGAROO RAT	*Dipodomys stephensi*
9	MERRIAM'S KANGAROO RAT	*Dipodomys merriami*
10	FRESNO KANGAROO RAT	*Dipodomys nitratoides*
11	SALT-MARSH HARVEST MOUSE	*Reithrodontomys raviventris*
12	DUSKY-FOOTED WOODRAT	*Neotoma fuscipes*
13	CALIFORNIA VOLE	*Microtus californicus*
14	RED FOX	*Vulpes vulpes*
15	KIT FOX	*Vulpes macrotis*
16	ISLAND GRAY FOX	*Urocyon littoralis*
17	WOLVERINE	*Gulo gulo*
18	SEA OTTER	*Enhydra lutris*
19	GUADALUPE FUR-SEAL	*Arctocephalus townsendi*
20	NORTHERN SEA-LION	*Eumetopias jubatus*
21	BIGHORN SHEEP	*Ovis canadensis*

	REPTILES	
1	DESERT TORTOISE	*Gopherus agassizii*
2	BAREFOOT GECKO	*Coleonyx switaki*
3	COACHELLA VALLEY FRINGE-TOED LIZARD	*Uma inornata*
4	BLUNT-NOSED LEOPARD LIZARD	*Gambelia sila*
5	ISLAND NIGHT LIZARD	*Xantusia riversiana*
6	RUBBER BOA	*Charina bottae*
7	STRIPED RACER	*Masticophis lateralis*
8	COMMON GARTER SNAKE	*Thamnophis sirtalis*
9	WESTERN AQUATIC GARTER SNAKE	*Thamnophis couchii*
10	GIANT GARTER SNAKE	*Thamnophis gigas*

Vector Abundance



Data Sources:
California Department of Water Resources Land Use Surveys
CA Department of Water Resources (Various)
Central Valley Vernal Pool Complexes (Holland)
Dr. Robert F. Holland & CA Department of Fish & Game (1998)
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CA Department of Fish and Game & Various Cooperators (1997)
Multi-source Land Cover Data (2002 v1)
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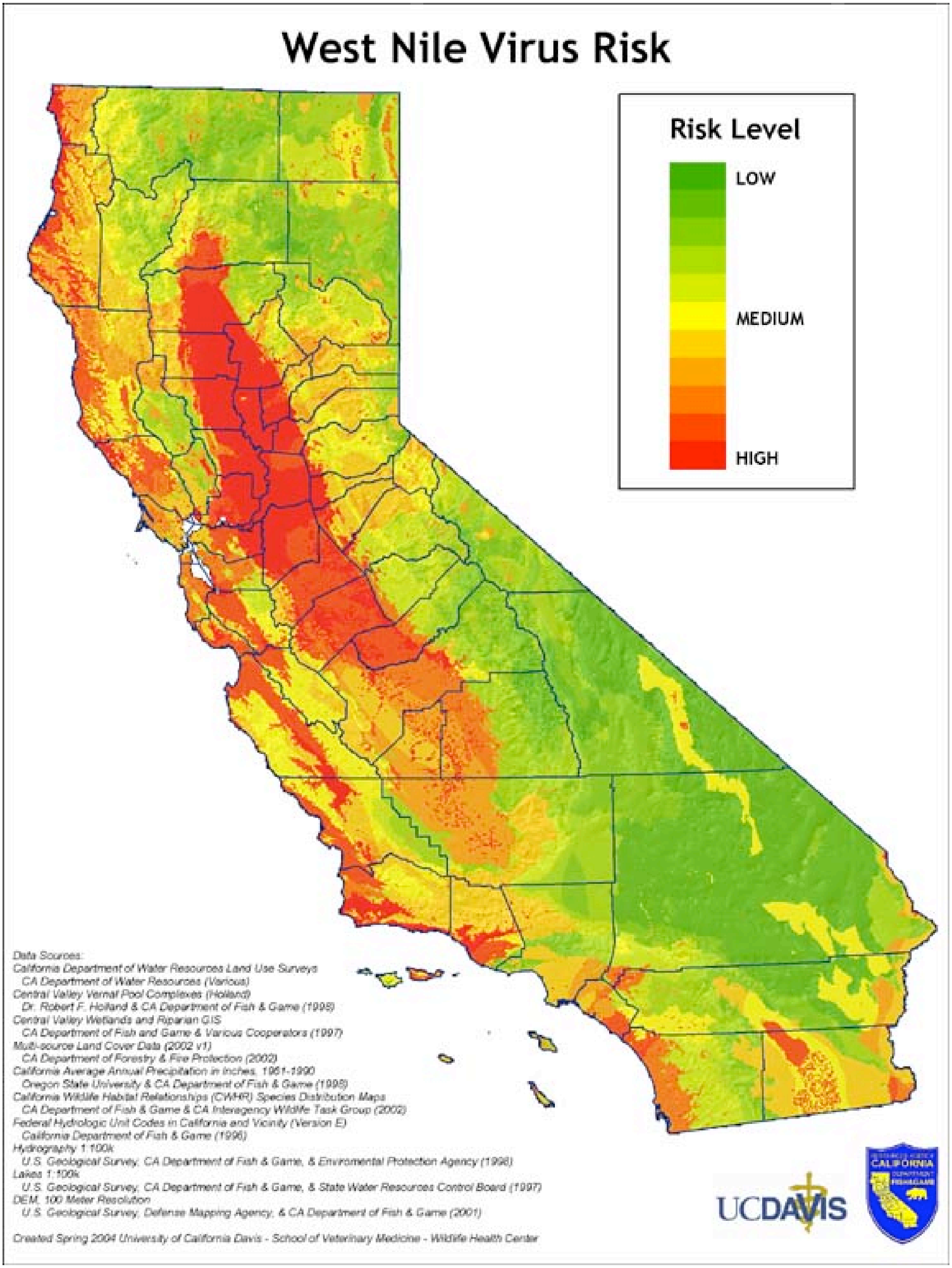

West Nile Virus Risk

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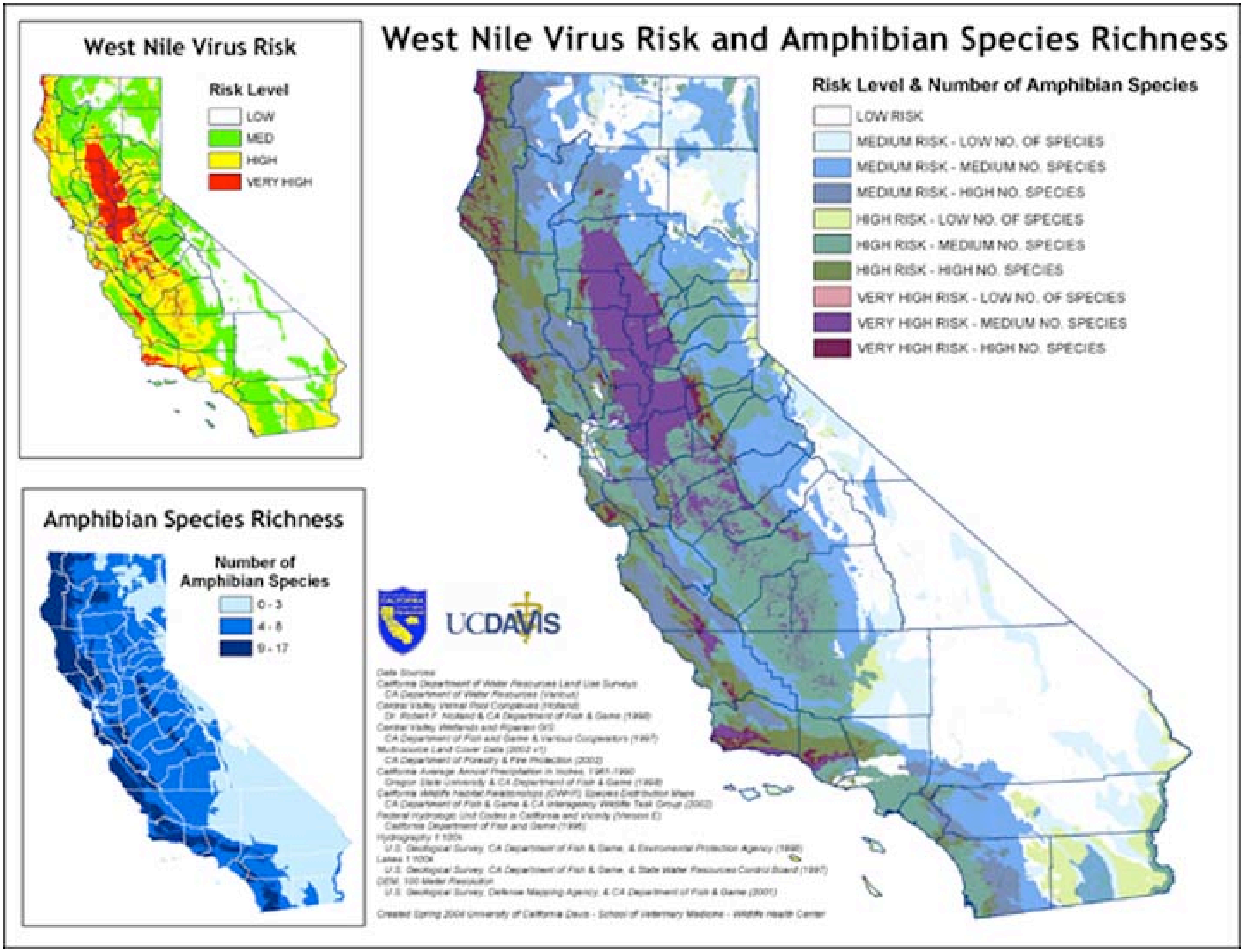

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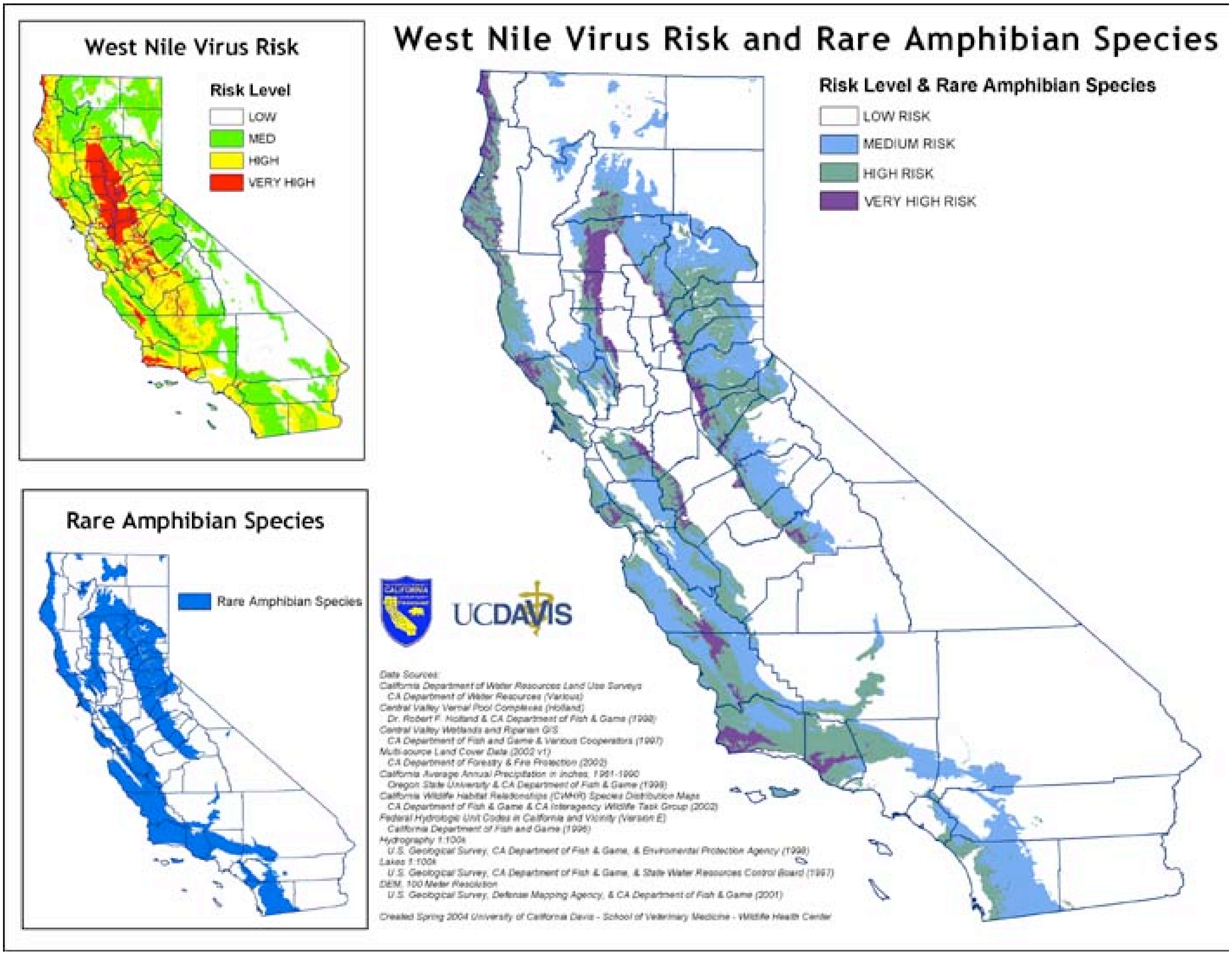

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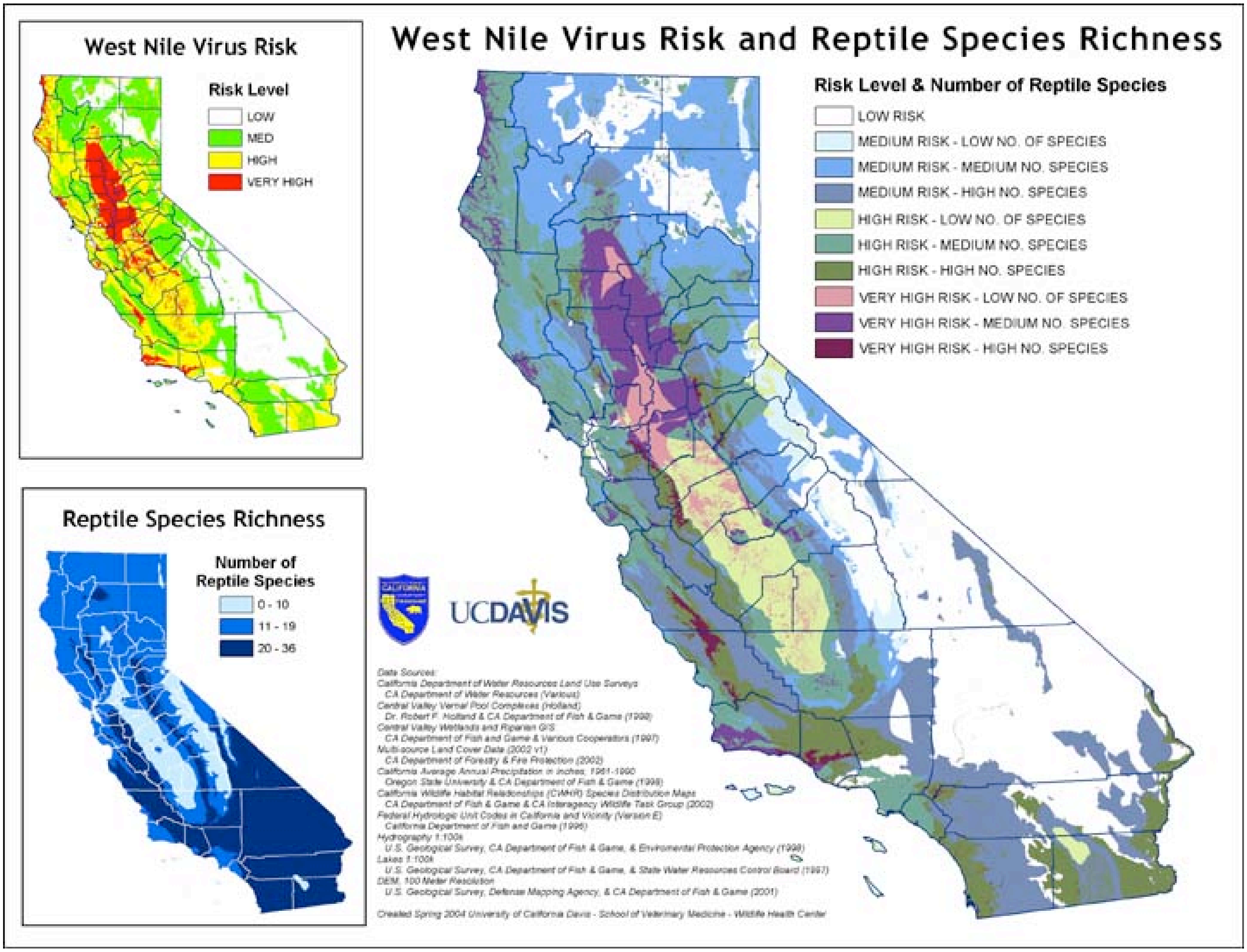

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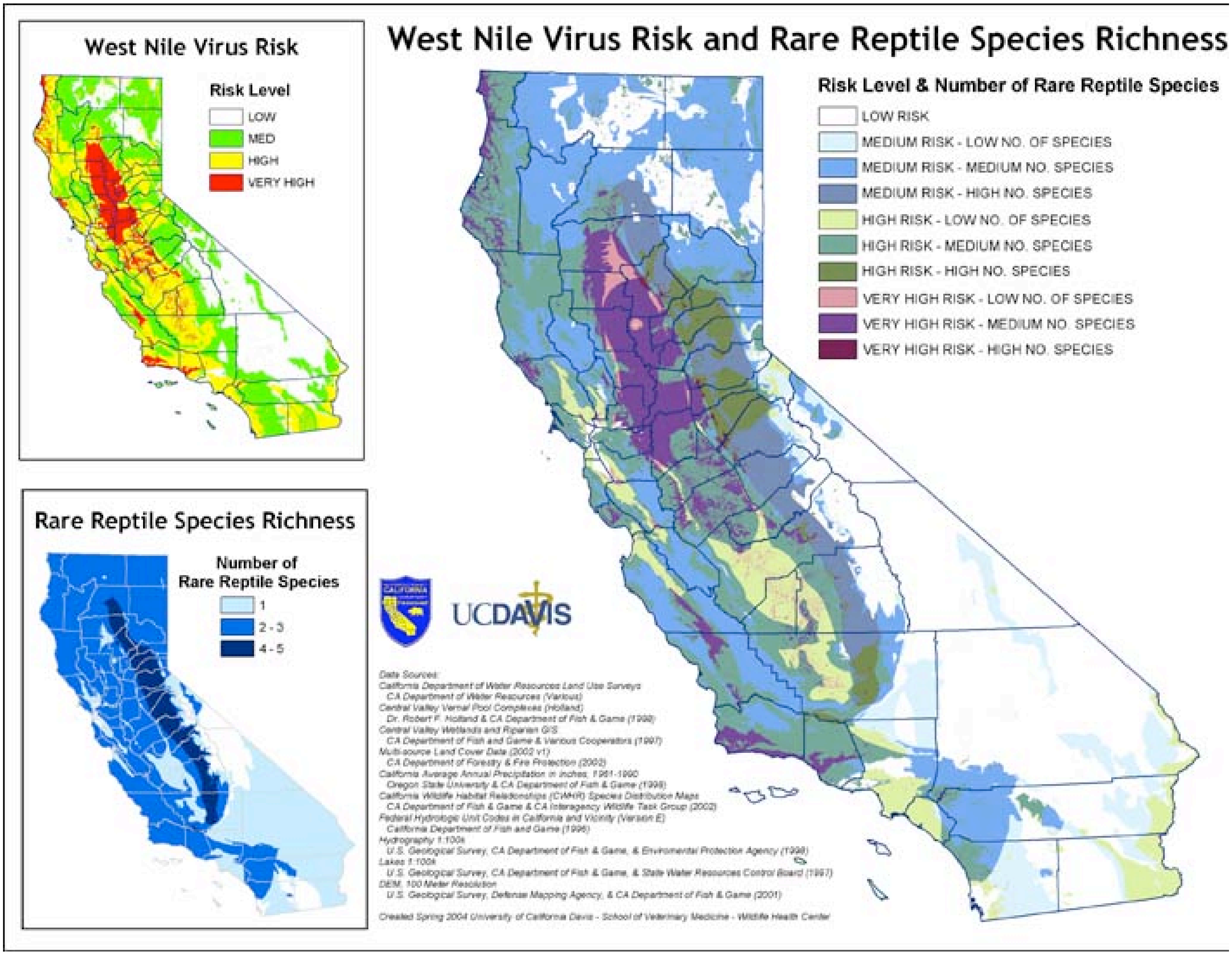

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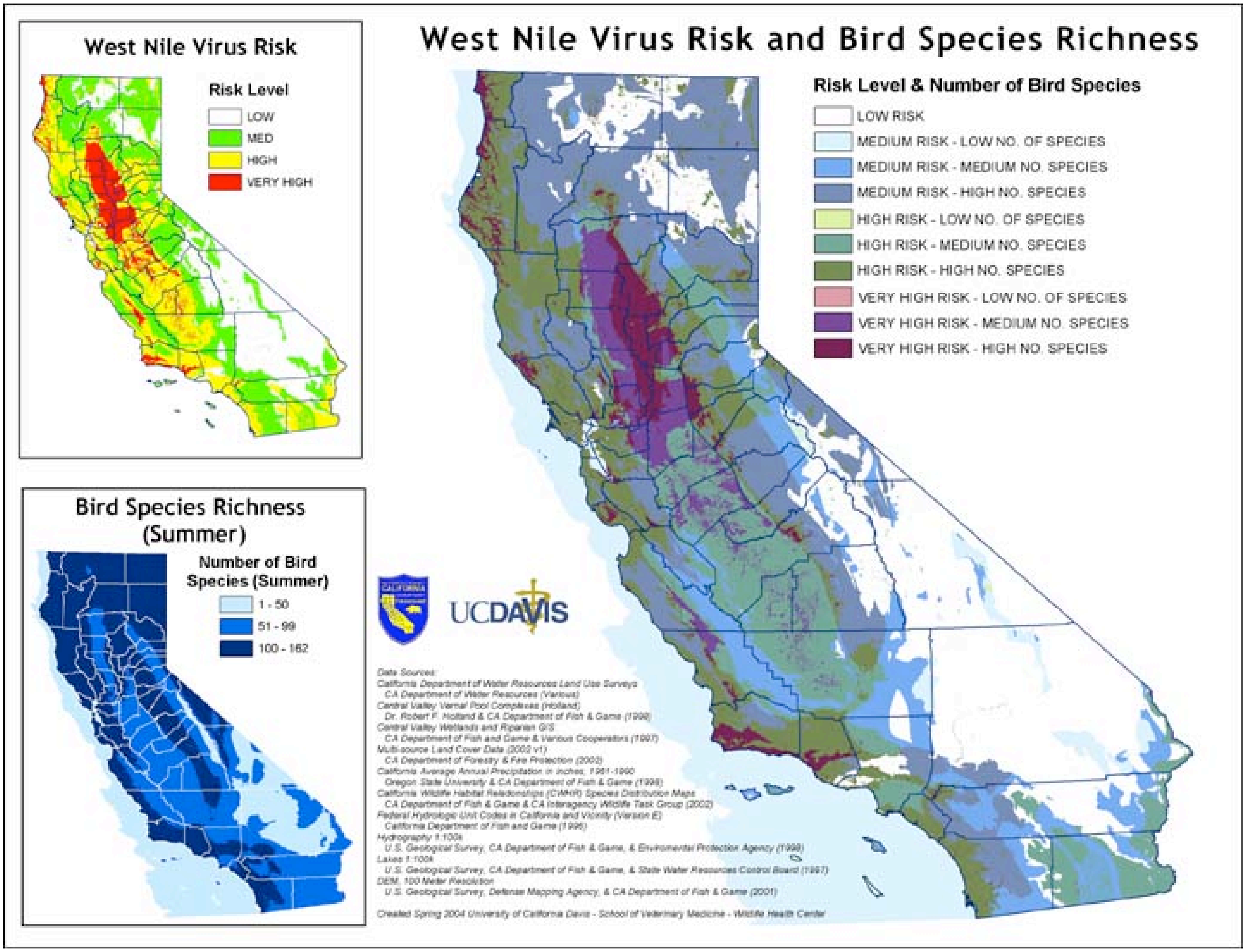

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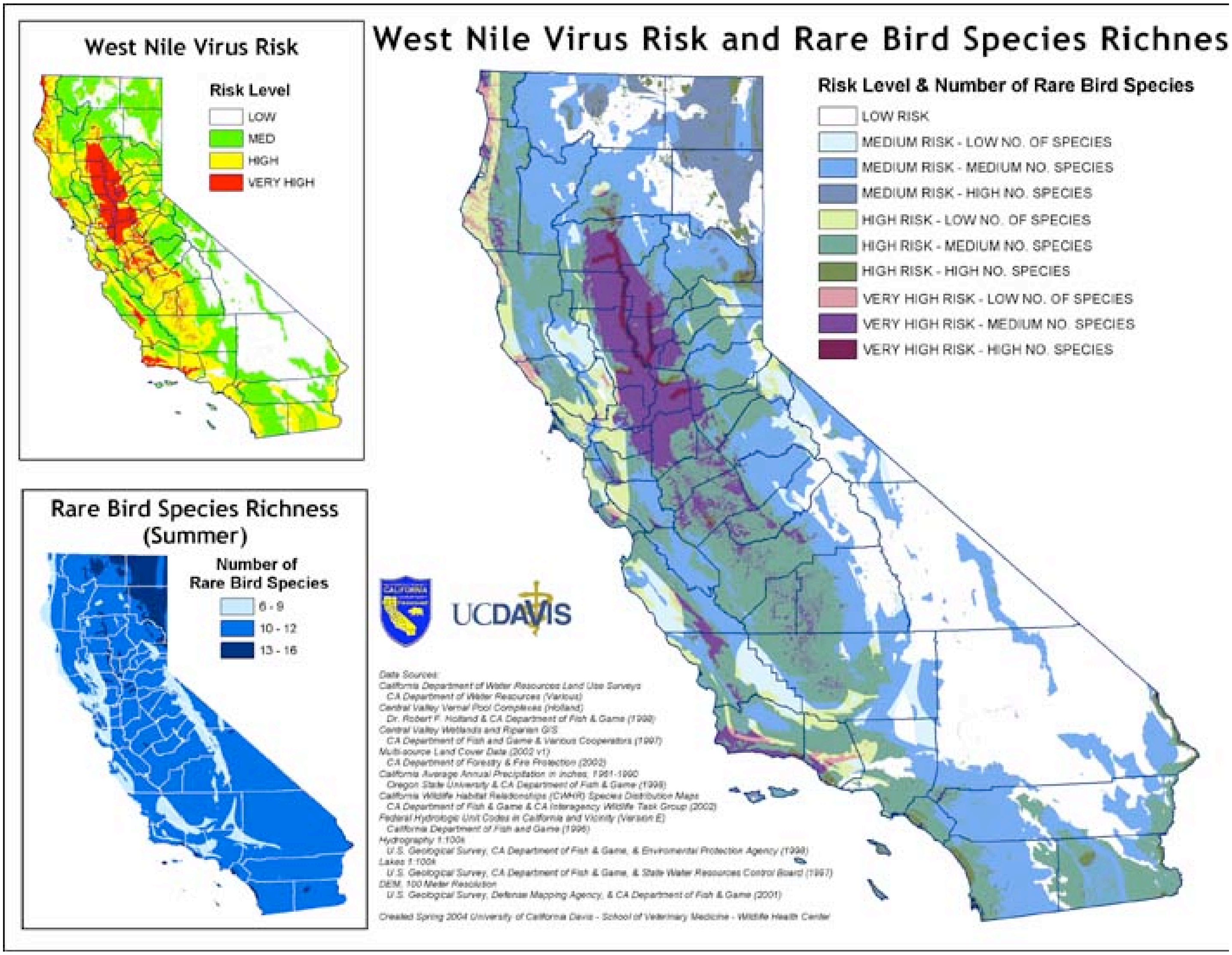

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Central Valley Vernal Pool Complexes (Holland)
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DEM, 100 Meter Resolution
U.S. Geological Survey, Defense Mapping Agency, & CA Department of Fish & Game (2001)

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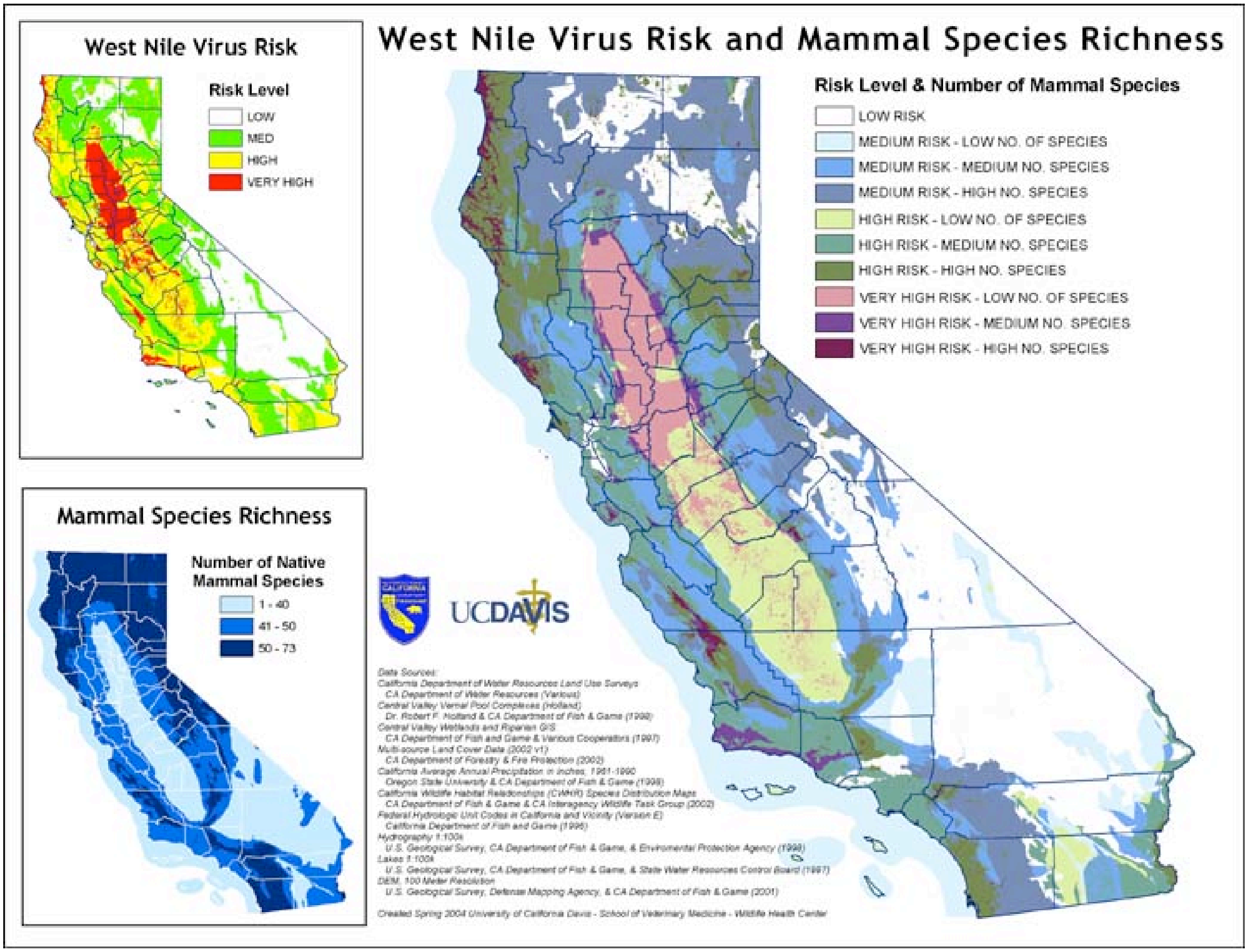

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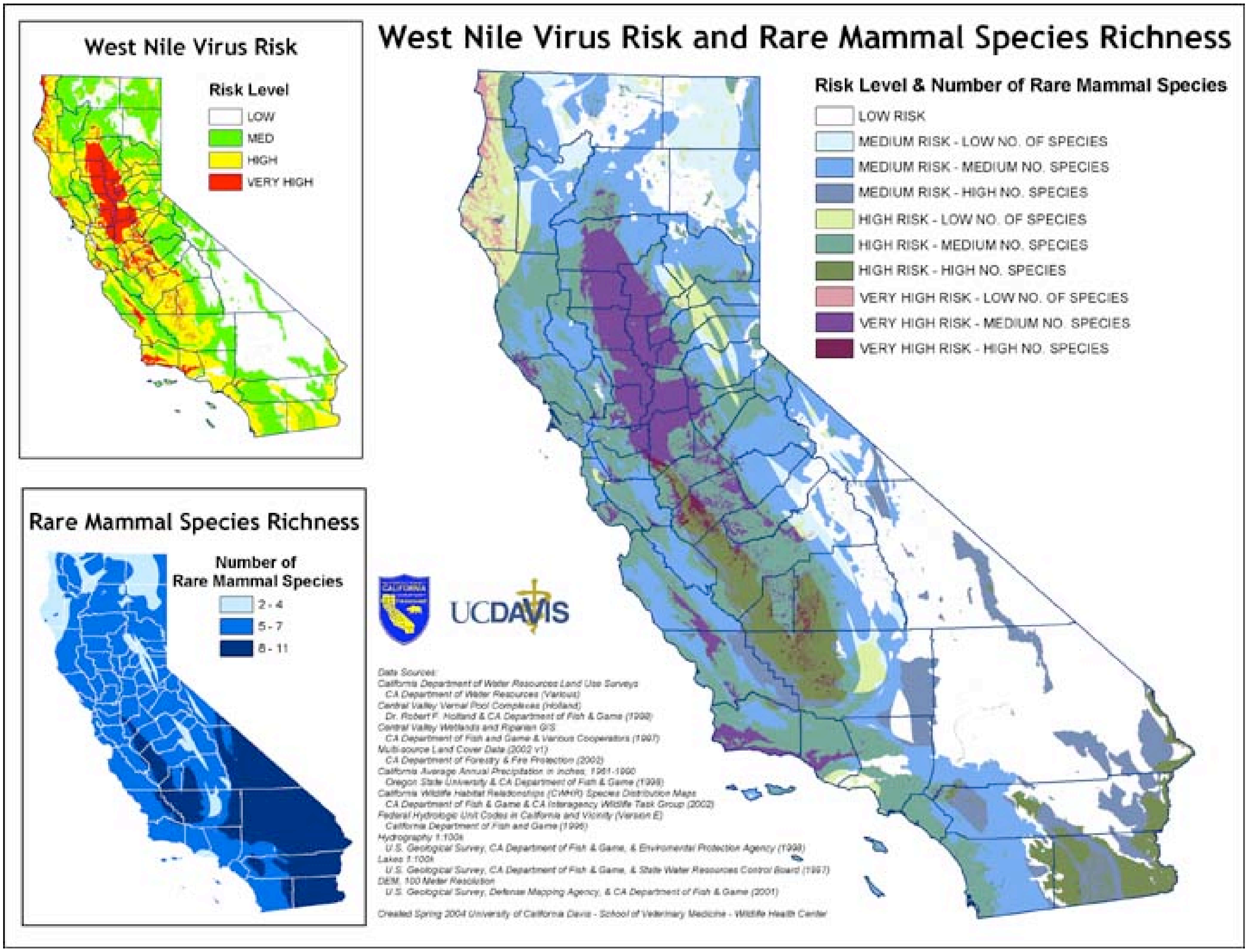

West Nile Virus Risk and Rare Mammal Species Richness

West Nile Virus Risk

Rare Mammal Species Richness

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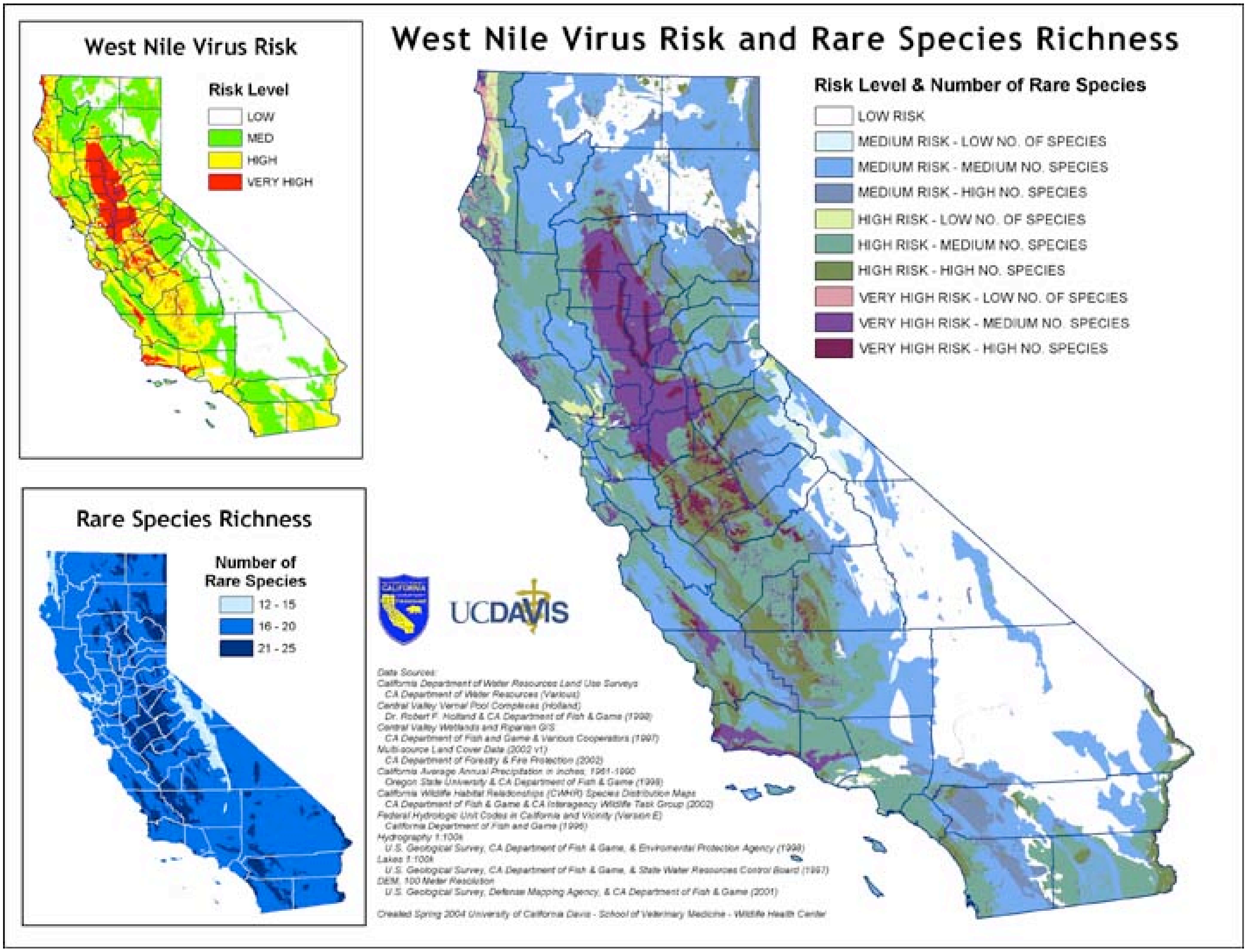

West Nile Virus Risk and Rare Species Richness

West Nile Virus Risk

Rare Species Richness

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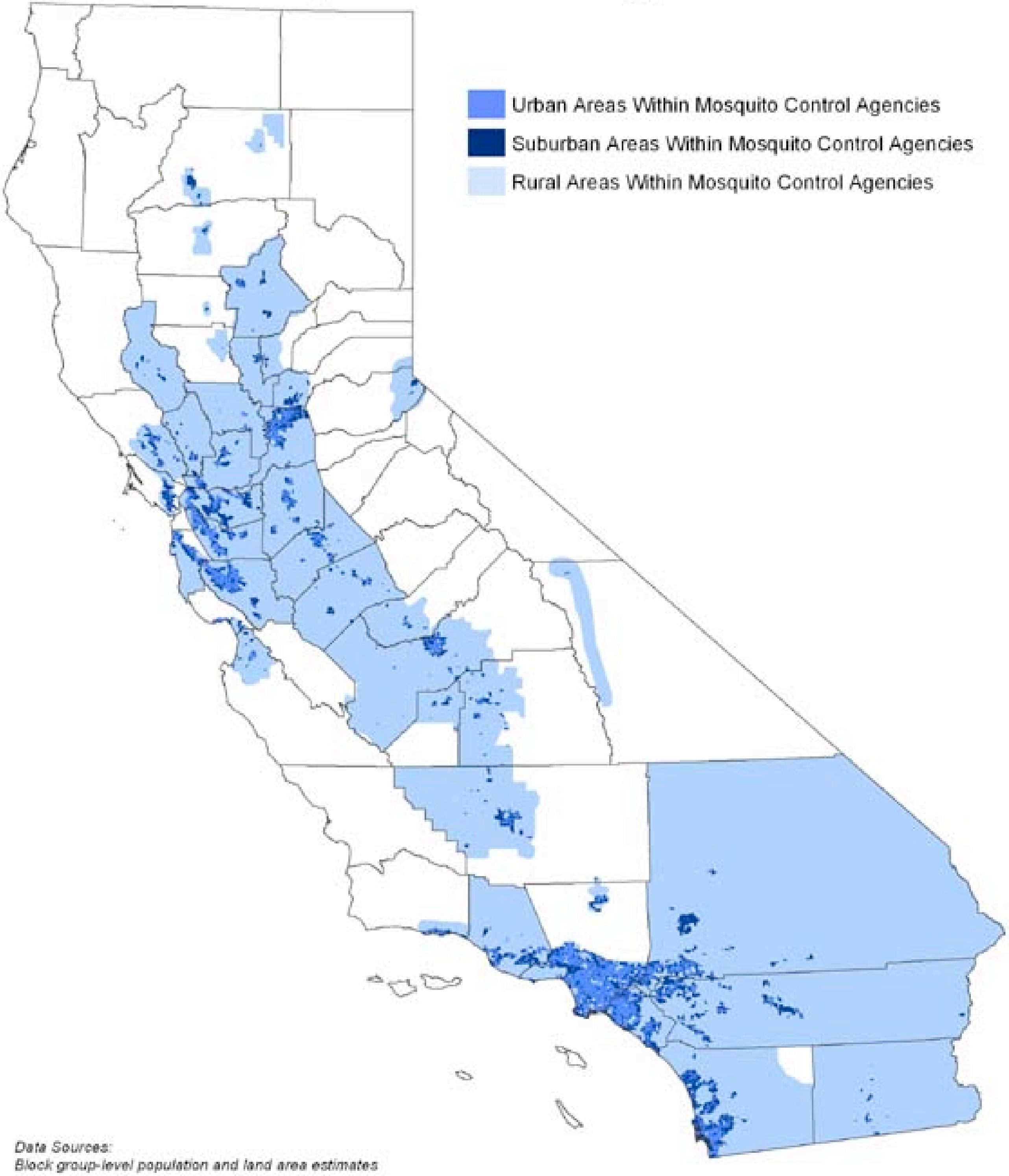
Human Population Within Mosquito Control Agencies



Data Sources:
Block group-level population and land area estimates
United States Census Bureau (2000)
Coverages of mosquito control agencies
Mosquito and Vector Control Association of California (Various)

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