Review

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Hantavirus Transmission Dynamics Concerning the United States: Epidemiology, Environmental Risk Factors, and Public Health Implications

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Abstract

Hantavirus pulmonary syndrome (HPS) is a severe disease first recognised in the United States in 1993, with a case fatality rate approaching 35–50%. Since the identification of Sin Nombre virus during the Four Corners outbreak, understanding the transmission dynamics and geographic distribution of hantaviruses has become critical for public health planning and prevention. This review synthesises evidence from ecological niche modelling, epidemiological surveillance, and environmental analyses to explain patterns of hantavirus occurrence in North America. The findings indicate that HPS risk is associated with dry climates, rural and peri-urban landscapes, rodent host ecology, and increased social vulnerability, with cases primarily concentrated in the western United States. We examine how environmental conditions, rodent ecology, human–rodent interactions, and socioeconomic factors interact to influence disease risk. This synthesis provides recommendations for reducing exposure in high-risk populations and regions.

Keywords: hantavirus pulmonary syndrome; emerging infectious disease; Sin Nombre virus; ecological niche modelling; rodent reservoir; zoonotic transmission

1. Background and Significance

Hantaviruses are members of the Hantaviridae family of enveloped, negative-sense, single-stranded RNA viruses. Persistent infections in certain rodent reservoir hosts, with which these viruses have coevolved across extended evolutionary periods, sustain these viruses in the natural world. Exposure to infected rodent waste can unintentionally infect humans and cause serious pandemic illnesses. In the Americas, hantaviruses are mostly linked to hantavirus pulmonary syndrome (HPS), a deadly respiratory disease that frequently results in respiratory failure and death. It is characterized by fever, myalgia, thrombocytopenia, and rapidly progressive non-cardiogenic pulmonary edema.

During the 1993 Four Corners outbreak in the southwestern United States, HPS initially attracted significant medical and public health attention. The outbreak began after a young Navajo man and his fiancée unexpectedly died of acute respiratory failure. Later epidemiological studies found more cases among young adults in Arizona, New Mexico, Colorado, and Utah who had previously been healthy. The Sin Nombre virus was identified as the cause of the epidemic [1] after a series of inexplicable severe respiratory diseases were identified by mid-1993. This incident was crucial to the identification of a new hantaviral illness in North America.

Hantaviruses are spherical, encapsulated virions with a diameter of 80–120 nm. Surface glycoprotein spikes embedded in the lipid membrane provide a distinctive grid-like pattern. Increased vascular permeability and pulmonary pathology seen in HPS are caused by these glycoproteins, which mediate viral attachment and passage into endothelial cells. The RNA-dependent RNA polymerase, glycoprotein precursor, and nucleocapsid protein are encoded by the three negative-sense RNA segments that

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make up the viral genome: large (L), medium (M), and small (S) [2]. The viral genome structure of hantaviruse is shown in Figure 1.

From an ecological and epidemiological standpoint, inhalation of aerosolized particles from rodent urine, saliva, or feces is the most prevalent way for people to contract the hantavirus, especially in enclosed or poorly ventilated areas. Cleaning rodent-infested houses, working in agriculture, and being exposed to work in rural areas are all linked to a higher risk of infection. Crucially, unlike several Old World hantaviruses, the Sin Nombre virus has not been observed to spread from person to person in the United States [3].

Indirect transmission paths are further facilitated by the fact that hantaviruses exhibit significant environmental stability and may continue to be contagious outside of the host under favorable temperature and humidity conditions. Although the virological literature [2] provides a thorough description of the structural and molecular features of hantaviruses, ecological interactions between rodent reservoir populations and human environmental exposure are the main factors influencing the dynamics of their transmission.

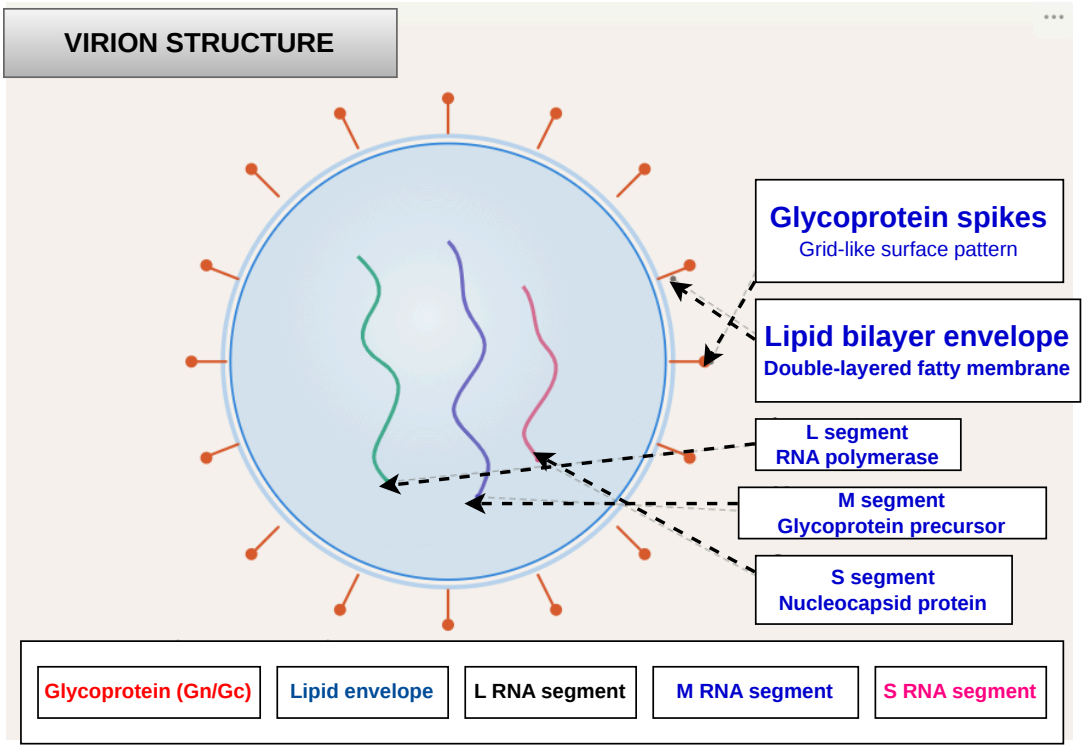

Figure 1. Structure of Hantavirus Viral Genome.

Hantavirus infections have continued to be a significant public health risk in the United States since HPS was first identified in 1993.The handtavrius spead in United States in shown in Figure 2. Over 800 confirmed cases were recorded by the end of 2022, most of which were categorized as HPS. The estimated case mortality rate was between 35 and 40 percent [4]. The severity of the illness highlights its importance as a rodent-borne zoonosis with significant clinical consequences, despite its relative rarity.

Growing evidence suggests that environmental and socioeconomic variables impact the emergence and spread of hantaviruses. Human exposure risk can be affected by changes in reservoir quantity and viral circulation caused by climate variability, land-use change, ecological disturbance, and rodent population dynamics. Furthermore, housing conditions, public awareness, and occupational activities significantly impact an individual's susceptibility to infection. Improving surveillance, risk assessment, and public health readiness requires an understanding of these interrelated ecological and societal factors [5].

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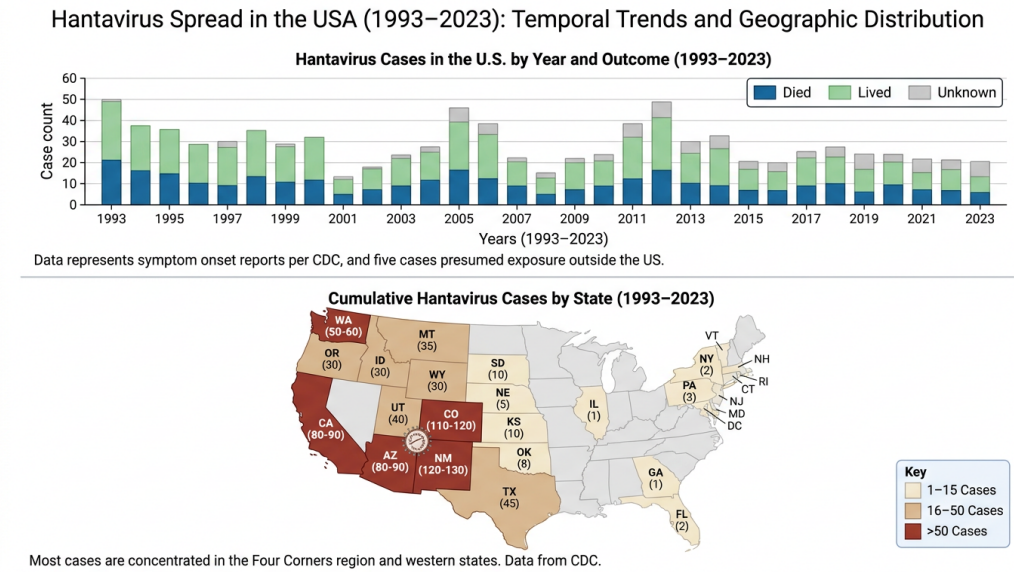

Figure 2. Hantavirus Spread in the USA, Temporal Trends and Geographical Distribution.

1.1. Objectives and Scope

This study integrates findings from epidemiological surveillance, ecological niche modelling, environmental investigations, and public health research to provide a complete overview of hantavirus transmission processes in the United States. The objective is to compile the most recent information on the biological, environmental, and socioeconomic factors that influence the establishment of hantaviruses and the risk of human infection.

Specifically, this review examines:

- The identity, ecology, and geographic distribution of rodent reservoir species associated with hantavirus transmission.
- The primary transmission pathways through which hantaviruses are transmitted from infected rodents to humans.
- The environmental and climatic conditions that influence hantavirus persistence and transmission dynamics.
- Geographic patterns of hantavirus risk across the United States.
- The influence of socioeconomic, occupational, and meteorological factors on human exposure risk.
- Current public health responses, prevention strategies, and surveillance systems used to reduce hantavirus outbreaks.

By synthesising evidence across multiple disciplines, this review aims to improve understanding of hantavirus epidemiology and support evidence-based public health strategies for disease prevention and risk mitigation.

2. Rodent Reservoirs and Virus Biology

2.1. Primary and Secondary Reservoir Species

In the United States, Sin Nombre virus is the primary cause of HPS. Its main reservoir is the deer mouse (Peromyscus maniculatus). The CDC identified this species as the main carrier on June 14, 1993. The deer mouse, found throughout North America, is the primary carrier of Sin Nombre virus [6].

Yet, hantavirus ecology in the Americas is more complex than a single virus–host relationship. Other Sin NoOther Sin Nombre virus variants that can cause HPS include the Monongahela and New York orthohantaviruses. The orthohantavirus is carried by the white-footed mouse (Peromyscus

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leucopus). Bayou and Black Creek Canal orthohantaviruses are considered separate species. Their hosts are the rice rat (Oryzomys palustris) and cotton rat (Sigmodon hispidus).

The deer mouse, white-footed mouse, cotton rat, and rice rat all transmit hantavirus pulmonary syndrome to humans. The deer mouThe deer mouse is found throughout North America; the cotton rat and rice rat range from the southeastern United States to South and Central America, respectively; and the white-footed mouse is distributed across much of the United States and Mexico. Tent Infection in Rodent Reservoirs A key aspect of hantavirus ecology is that infected rodents do not appear sick; instead, they carry lifelong infections [6]. The reasons for this have been studied in persistently infected newborn mice. Scientists have shown that CD8+ T cells—a type of white blood cell involved in immune defence—are essential for clearing infections. In persistently infected newborn mice, although they have high levels of antibodies that neutralise the virus, they lack functioning virus-specific CD8+ T cells during the period the infection is maintained, suggesting that these immune responses are crucial for eliminating the virus but are absent during ongoing infection [7].

Hantaviruses and their rodent hosts have coevolved over tens of millions of years. This has made the viruses well-adapted to maintaining chronic infections in natural reservoirs, while causing severe disease in humans. This relationship explains why rodents can have high virus prevalence without suffering population-level effects.

Instead of spreading directly from person to person, hantaviruses are mainly transferred from infected rodents to humans through environmental exposure. Rats and deer mice *Peromyscus maniculatus* are among the rodent reservoir species that carry the virus asymptomatically and excrete viral particles in their urine, saliva, and feces [8]. Humans may inhale infectious particles and get an infection when contaminated materials dry and become aerosolized. Although rare, direct transmission by rodent bites is a possibility [3]. Only Andes virus strains in South America have been shown to be capable of person-to-person transmission, which is incredibly uncommon [9]. Figure 3 illustrates how the hantavirus transmission cycle operates. Farmers, forestry workers, and military personnel are among those who are thought to be at a higher risk of exposure since they operate in rural and outdoor situations [10].

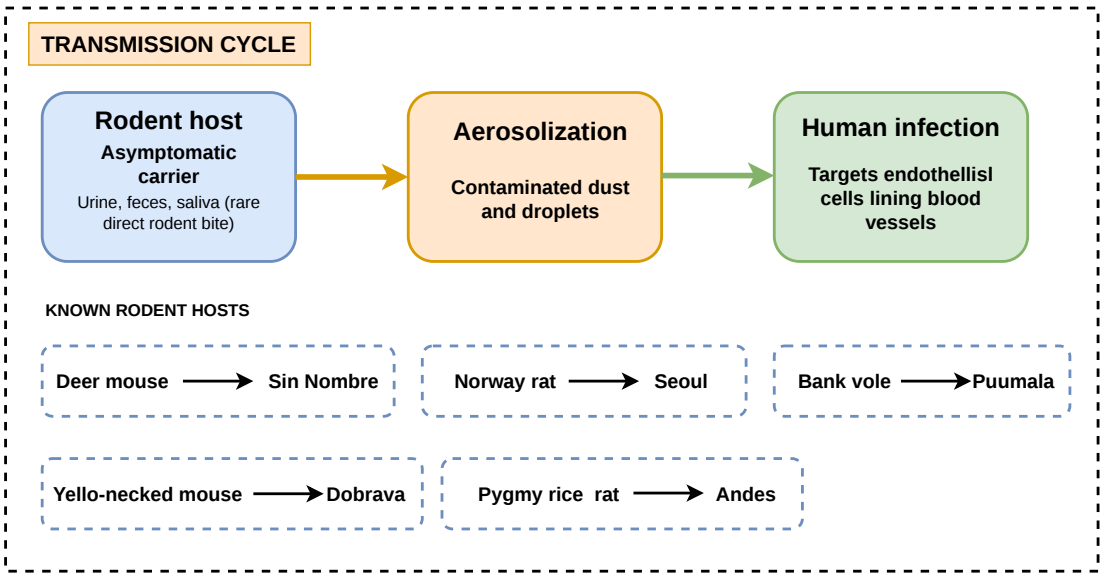

Figure 3. Hantavirus Transmission Cycle.

2.2. Aerosolisation as Primary Transmission Route

The primary method of hantavirus transmission to humans is thought to be aerosolisation. Saliva, urine, and feces from infected rodents can spread the virus, and airborne viral particles can be released when contaminated materials are disturbed [8]. These aerosolized particles may then be inadvertently

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inhaled by humans, leading to illness. In enclosed or poorly ventilated areas where contaminated dust may build up, this type of indirect environmental transmission is especially crucial.

Although it is uncommon, hantavirus infection can also result from direct contact of contaminated material with mucous membranes or from rodent bites that tear the skin. However compared to airborne environmental exposure, these routes are much less prevalent [3].

2.3. Environmental Persistence and Infectivity

The dynamics of hantavirus transmission are significantly influenced by environmental persistence. Hantaviruses may remain for a long time in contaminated surfaces and rodent excrement under favorable environmental circumstances [11]. Human exposure to contaminated aerosolized particles may be more likely in areas of the western United States that are frequently dry and dusty.

Viral survival outside of the host is influenced by environmental factors such temperature, humidity, and UV radiation. Reduced moisture levels in arid areas may prolong the persistence of infectious rat waste in storage buildings, cabins, and other human-frequented confined spaces [12]. Deer mice are nocturnal and often live in sheltered areas where virus particles may be preserved from environmental damage.

2.4. High-Risk Activities and Exposure Settings

Most hantavirus infections result from environmental exposure occurring in residential, occupational, or recreational settings. Several activities and environments are associated with increased transmission risk:

- Occupational exposure in farming, forestry, construction, and military activities conducted in rural or rodent-infested environments [13]
- Residential exposure in poorly maintained buildings with structural openings that permit rodent entry and accumulation of rodent excreta [3]
- Recreational exposure in cabins, campsites, sheds, and shelters where rodent populations may be established [8]
- Disturbance-related exposure during cleaning or renovation of enclosed spaces contaminated with rodent droppings, urine, or nesting materials, which may aerosolise infectious particles [3]

3. Geographic Distribution and Epidemiological Patterns

3.1. Spatial Distribution of Cases

The western states of the United States have a significant and well-established geographic concentration of hantavirus cases. According to surveillance data from 1993 to 2022, this region accounts for most reported cases of hantavirus pulmonary syndrome (HPS), whereas the eastern United States reports relatively few infections. Differences in the distribution of reservoir rodent species, especially the deer mouse (Peromyscus maniculatus), which is the main host of the Sin Nombre virus in North America, and environmental factors that affect viral persistence and human-rodent contact rates are the main causes of this spatial heterogeneity.

The fundamental epidemiological paradigm for comprehending hantavirus emergence in North America was established by the first Four Corners outbreak, which occurred between 1993 and 1995. More than 45 confirmed deaths in the southwestern United States during this outbreak period were attributed to the Sin Nombre virus [10]. The concentration of instances in semi-arid and rural areas emphasized the significance of ecological interfaces where rodent habitats and human settlement coexist.

More generally, land use change, climatic variability, and ecological niche restrictions all influence patterns of spatial distribution. Higher hantavirus risk is typically seen in areas with semi-arid or arid climates, sporadic precipitation, and appropriate rodent habitat structure. In contrast, there is a significantly lower incidence of HPS in the eastern United States due to distinct rodent communities and ecological factors that are less conducive to the preservation of the Sin Nombre virus.

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3.2. Temporal Patterns and Seasonal Variation

Strong interannual variability in hantavirus incidence is caused by changes in rodent population density, climate variability, and human exposure behaviour. The Centers for Disease Control and Prevention's surveillance records show that the number of cases varies significantly across years, with occasional epidemic maxima coinciding with times of higher rodent population and improved human–environment contact.

Increased precipitation in the southwestern United States has been linked to large-scale climate oscillations, especially El Niño–Southern Oscillation (ENSO) incidents. Rodent populations have more access to food as a result of these precipitation events' promotion of vegetation development. Rodent population growth may result from this bottom-up ecological effect, raising the danger of overflow by increasing the likelihood that humans will come into contact with contaminated excrement. As an example of how climatic anomalies can indirectly impact the emergence of zoonotic diseases through ecological amplification processes, the 1991–1992 El Niño episode is commonly regarded as a major environmental antecedent to the 1993 Four Corners outbreak [12].

Seasonal human behavior also affects temporal variance. During the spring and summer, when outdoor activities, agricultural labor, and cleaning of rarely used buildings like cabins or sheds are more prevalent, increased exposure is usually noted. Seasonal risk fluctuation is further influenced by the intersection of these behavioral patterns with times of higher rodent activity.

In general, rather than a single deterministic source, the temporal and spatial patterns of hantavirus disease reflect a complex interaction between ecological dynamics, climate variability, and human land-use practices.

4. Environmental and Ecological Drivers of Transmission

4.1. Climate as a Risk Factor

Climate conditions influence rat population ecology, environmental viral persistence, and human exposure patterns, all of which have a significant impact on hantavirus transmission. The distribution of hantaviruses in the United States is closely linked to climatic variability, specifically precipitation regimes and temperature-related variables, according to spatial risk modelling [14].

The most significant climatic predictor of hantavirus risk, according to Glass et al., is precipitation (26.1%), followed by temperature range (23.5%) and maximum temperature (19.4%) [14]. These results suggest that rather than a single dominant factor, hantavirus risk is structured by interacting environmental circumstances. In particular, arid and semi-arid regions with high temperature variability and minimal rainfall are linked to increased risk.

These climatic associations reflect underlying ecological processes governing rodent reservoir dynamics and virus transmission. Climate variability influences:

- **Rodent population dynamics:** Precipitation regulates primary productivity and vegetation growth, thereby controlling food availability and rodent population density [8].
- **Environmental persistence:** Low humidity and dry conditions may enhance the survival of hantaviruses in rodent excreta and contaminated dust [12].
- **Human exposure pathways:** Arid environments increase dust generation during occupational and domestic activities, facilitating inhalation of aerosolised viral particles [8].
- **Seasonal and behavioural variation:** Climatic conditions influence both rodent activity patterns and human outdoor behaviour, altering contact rates [12].

Overall, climate acts indirectly on hantavirus transmission through ecological amplification processes that regulate host abundance and environmental exposure risk rather than through direct effects on viral activity.

4.2. Land Use and Habitat Characteristics

Land-use patterns are important factors of hantavirus transmission because they influence both rodent habitat appropriateness and the frequency of human-wildlife encounters. Increased rodent

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diversity, arid climates, and land-use categories linked to low-intensity human development are characteristics of places with elevated hantavirus risk, according to spatial modelling studies [14].

Developed open spaces and low-intensity developed regions in particular have been found to be important indicators of elevated risk. These landscapes are examples of biological transition zones where natural rodent habitats and human settlements coexist, fostering circumstances that encourage spillover events. Human exposure to reservoir hosts is increased by habitat fragmentation and land-use change in other developing zoonoses [15].

The impact of anthropogenic environmental change on the onset of disease is reflected in the epidemiological significance of land-use variables. The likelihood of human contact with infected rodent populations is increased by land change, agricultural development, and settlement into previously unaltered ecosystems. As a result, these fringe or edge habitats are acknowledged as important interfaces for zoonotic spillover occurrences [15].

4.3. Rodent Diversity and Community Composition

Hantavirus dynamics have been extended beyond a single-host paradigm by recent ecological research to include multi-host and community-level phenomena. In ecological models, rodent species richness has been positively correlated with hantavirus risk, indicating that higher host variety may improve pathogen maintenance and overflow potential through improved ecological connectedness among species [16].

Using quantitative polymerase chain reaction (qPCR), surveillance data from eastern New Mexico revealed Sin Nombre virus RNA in 16 rodent species, and serological evidence of hantavirus exposure was found in 15 species, including a number of previously unidentified hosts [17]. These results imply that hantavirus exposure may occur across a wider spectrum of rodent species than previously thought, even when genetic or serological detection does not always prove reservoir competence.

Increased rodent variety may raise the risk of transmission from an ecological standpoint by increasing the number of possible host-pathogen contacts and promoting indirect transmission pathways. Hantavirus dynamics may involve a network of primary and secondary hosts that contribute to viral circulation at the ecosystem level rather than being sustained solely within a single reservoir species [16].

4.4. Clinical and Ecological Context of Hantavirus Syndromes

Hantavirus pulmonary syndrome (HPS) and hemorrhagic fever with renal syndrome (HFRS) are the two main clinical syndromes caused by hantaviruses, as shown in Figure 4. While HFRS largely affects renal function and is linked to hemorrhagic symptoms and acute damage to the kidneys HPS principally affects the respiratory system and is marked by severe pulmonary edema [18].

Despite the fact that both diseases first manifest as non-specific febrile fever, their clinical course and mortality rates differ markedly. While HFRS normally shows lower mortality, often ranging from 1–15% depending on viral species and healthcare availability, HPS is linked to case fatality rates of about 40–60% [19].

These variations highlight the significance of ecological environment in influencing disease severity and dissemination and show unique hantavirus–host coevolutionary connections across geographic locations. In order to evaluate both spatial epidemiological patterns and the establishment of clinically diverse hantavirus illnesses across geographical locations, it is imperative to comprehend these ecological forces.

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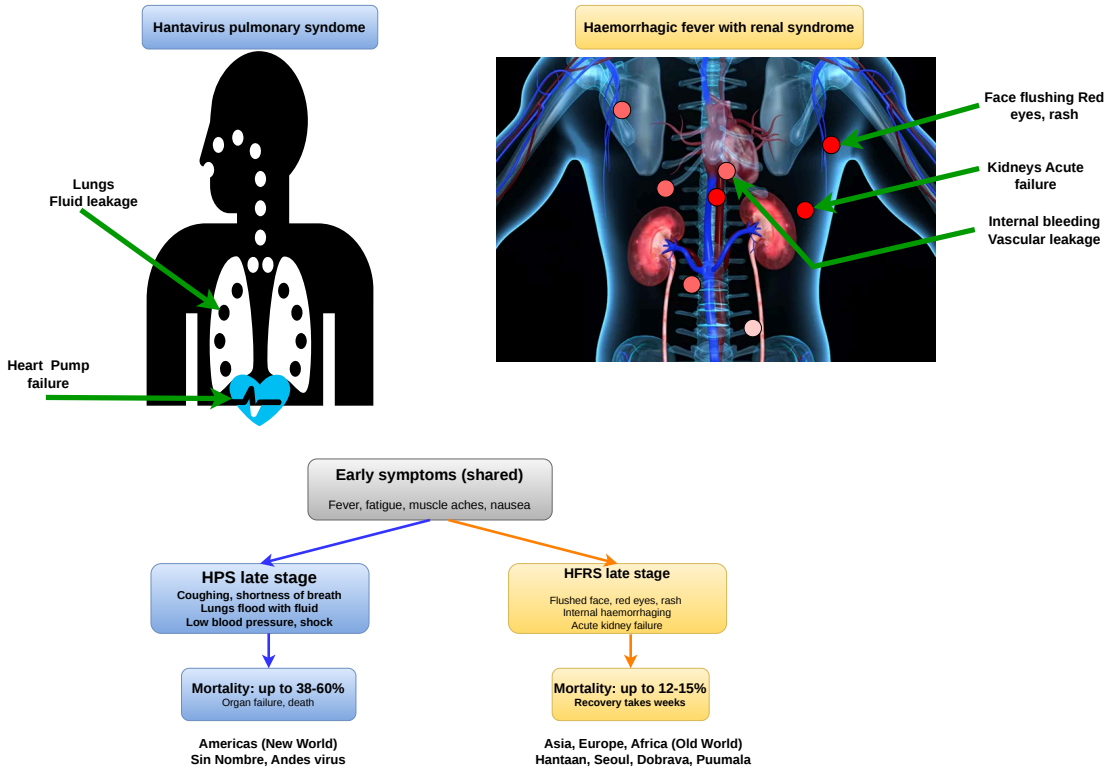

Figure 4. Hantavirus Syndromes.

5. Socioeconomic Factors and Vulnerability

5.1. Social Vulnerability Index and Hantavirus Risk

The impact of socioeconomic factors on exposure risk and disease consequences is a significant but frequently overlooked aspect of hantavirus transmission. Social vulnerability has a significant impact on where infections occur and which communities are most impacted, in addition to ecological factors like rodent abundance and climate fluctuation. Household composition accounted for 46.1% of variable importance, followed by minority status at 25.8% and housing type and transportation at 19.8%, according to studies using the Social Vulnerability Index (SVI) to assess hantavirus risk in the western United States [14].

Individuals with disabilities, single-parent homes, persons 65 years of age and older, and dependent children under the age of 18 were all included in the household composition. Because these demographic traits are frequently linked to less mobility, lower income, and restricted access to healthcare and preventive resources, they may make people more vulnerable. Prior research also showed that a higher risk of contracting the hantavirus was linked to dwellings with structural flaws, such as holes or gaps that allow rodents to enter, as well as families with higher rodent population [20].

The concentration of poverty and poor living conditions in rural western U.S. areas, where hantavirus reservoir species like the deer mouse (Peromyscus maniculatus) are common, is probably reflected in these socioeconomic correlations. Inadequate housing infrastructure makes it easier for rodents to enter and build nests, which raises the risk of contaminated urine, saliva, or faeces coming into touch with people. Due to a lack of funding, many low-income rural areas may not have access to public health education, pest control methods, or rodent-proof buildings, which increases the risk of exposure.

Socioeconomic vulnerability may have an impact on disease outcomes in addition to exposure probability. Due to the rapid course of hantavirus cardiopulmonary syndrome (HCPS), rural communities frequently experience insufficient intensive care capacity, delayed diagnosis, and restricted access to healthcare facilities. As a result, socioeconomic deprivation is linked to greater death rates, worse clinical outcomes, and an increased risk of infection.

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5.2. Occupational and Residential Risk Factors

Certain populations are exposed to hantavirus at a disproportionately high rate due to their jobs and living situations. Confined or poorly ventilated areas, such as cabins, barns, sheds and abandoned structures with rat infestations, are highly linked to transmission. Humans are usually infected when contaminated urine, saliva, or faeces from infected rodents are disturbed, allowing viral particles to become aerosolised and inhaled [21]. These environmental factors are especially favourable for the spread of dust during dust-producing tasks like cleaning, sweeping, or structural disruption in enclosed areas.

Agricultural workers are at high risk because to their frequent exposure to rodent habitats such as grain storage facilities, animal barns, and agricultural fields [21]. When restoring or demolishing older buildings that have been inhabited by rats, construction and repair workers may also be exposed. Forestry workers, campers, military personnel, and field researchers working in endemic rural areas are also at greater risk due to frequent interaction with natural rodent habitats and undisturbed surroundings where reservoir species are widespread [22].

Risk heterogeneity is further influenced by residential location. People who live in isolated rural areas are more likely to be close to reservoir populations, like as deer mice (Peromyscus maniculatus), and may encounter rodent intrusion into their homes and storage facilities. Additionally, seasonal patterns of exposure have been documented, especially during activities that have been repeatedly linked to hantavirus outbreaks and sporadic cases in North America, such as cleaning rarely used buildings or opening cabins after extended closure [20].

Overall, the multifactorial risk landscape created by rural living, environmental factors, and occupational exposure contributes to the uneven geographic distribution of hantavirus infections and emphasises the significance of both structural and behavioural preventive measures.

6. Regional Variation in Transmission Drivers

6.1. Western United States Hantavirus Epidemiology

About 93% of recorded cases of hantavirus cardiopulmonary syndrome (HCPS) occur in states west of the Mississippi River [4]. In the United States, hantavirus disease is primarily found in the western region. The cumulative effects of reservoir ecology, climate variability, land-use patterns, and human behavioural aspects that all produce favourable conditions for zoonotic spillover are shown in this pronounced spatial clustering.

The deer mouse (*Peromyscus maniculatus*) [23] is the primary carrier of the Sin Nombre virus (SNV), the primary etiological agent of HCPS in North America. Due to their great adaptability and widespread distribution in rural, semi-arid, and alpine habitats, deer mice contribute to the region's vast geographic distribution of disease risk.

Central Colorado, northern New Mexico, Utah, southern California, eastern Washington, and the Snake River Valley of Idaho have all been identified as regions with increased hantavirus risk by spatial risk modelling studies [4]. Open and low-intensity developed landscapes, such as suburban and transit corridor environments where human development increasingly overlaps with reservoir ecosystems, have also been linked to increased relative risk. The productivity of vegetation and the availability of food for rats are two more ways that climate variability affects transmission dynamics. In the southwestern United States, periods of higher precipitation linked to El Niño occurrences have been associated with increases in rodent population density and consequent increases in human hantavirus cases [24].

In western environments, disease amplification may also be influenced by rodent community composition and biodiversity. It has been suggested that higher levels of Sin Nombre virus circulation among deer mouse populations are facilitated by increased rodent richness, increasing the probability of human exposure [4]. In rural and peri-domestic environments, when rodent penetration into homes, cabins, sheds, and storage structures allows contact with contaminated excreta, human illnesses frequently occur.

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6.2. Eastern United States and Alternative Reservoirs

Despite the fact that hantavirus disease has traditionally been thought of as a western U.S. phenomenon, there is growing evidence that different orthohantaviruses exist in the eastern U.S., driven by different reservoir species, ecological conditions, and habitat characteristics [25].

Eastern U.S. risk models highlight the significance of woody wetlands, pasture/hay landscapes, shrub/scrub habitats, and wooded ecosystems, in contrast to the western U.S., where hantavirus ecology is dominated by dry grasslands and semi-arid habitats [4]. The ecology of alternative hantavirus reservoir species that have adapted to damp and wetland habitats is reflected in these environmental connections.

Bayou orthohantavirus is a significant eastern hantavirus that is mostly linked to the marsh rice rat (Oryzomys palustris), a semi-aquatic rodent found in the Southeast of the United States [26]. The high correlation between wetland-associated land cover and disease risk in southeastern regions can be explained by the presence of marsh rice rats in swamps, marshes, wetlands, and coastal grasslands. Similar to this, the Black Creek Canal virus was initially discovered in Florida after HCPS investigations [25]. It is linked to the hispid cotton rat (*Sigmodon hispidus*).

Prospect Hill virus, Bloodland Lake virus, New York virus, Monongahela virus, and Blue River virus are among the many other orthohantaviruses found in the eastern United States. Many of these viruses are maintained in rodent hosts that are geographically limited [8,23]. The prevalence of these viruses indicates the significant ecological diversity of hantaviruses throughout North America, even though some of them are not frequently linked to serious human illness.

The relevance of localised ecological circumstances in influencing hantavirus transmission dynamics is shown by the different reservoir species and habitat preferences between eastern and western regions. Thus, the spatial heterogeneity of hantavirus risk across the United States is significantly influenced by regional differences in land cover, climate, rodent biodiversity, and human land use.

7. Ecological Niche Modelling and Risk Assessment

7.1. Maxent Modelling Approaches

Maximum entropy (Maxent) algorithms have been used more frequently in recent ecological specific modelling studies to combine diverse datasets, such as socioeconomic indicators, land use patterns, climate variables, and rodent distribution data, into cohesive spatial risk frameworks for hantavirus transmission. Maxent has been frequently utilised in zoonotic disease ecology to predict habitat appropriateness and potential spillover risk under incomplete surveillance settings, and it is especially well suited for presence-only epidemiology data [27].

These models capture complicated nonlinear interactions among predictors and estimate relative hantavirus risk over wide geographic areas by combining environmental appropriateness with human and ecological causes. When it comes to hantavirus, these modelling frameworks usually include climate variables (like temperature and precipitation), elevation, land cover structure, and indicators of human disturbance like low-density residential development and agricultural expansion [28]. To more accurately estimate transmission potential, some studies also include rodent abundance or habitat appropriateness for reservoir species such textitPeromyscus maniculatus as a biological layer [29].

From a conceptual standpoint, these models operationalise disease risk through the interaction of three core components:

- **Hazard**: presence and infection prevalence of hantavirus in rodent reservoir populations [23]
- **Exposure**: likelihood of human contact with contaminated rodent excreta in peri-domestic or occupational environments [20]
- **Vulnerability**: susceptibility shaped by sociodemographic and socioeconomic factors such as housing quality, occupation, and access to healthcare [14]

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7.2. Model Performance and Uncertainty

In the western United States, where case incidence is rather high and geographic clustering is prominent, ecological specialisation models trained on hantavirus case data from 1993 to 2022 have shown moderate to strong predictive performance [4,24]. Model results in these regions are more stable due to the larger availability of confirmed human cases and a more complete ecological understanding of Sin Nombre virus transmission patterns.

In contrast, there are fewer and geographically scattered recorded examples in the eastern United States, where model performance is typically less reliable. In particular, when modelling systems containing numerous hantavirus species and reservoir hosts with varied biological areas, this results in increased parameter uncertainty and decreased prediction confidence [25]. Inferring actual transmission patterns is made more difficult by the lower signal-to-noise ratio in case data from eastern regions, which reflects both lower incidence and possible underdiagnosis.

Despite these drawbacks, comparative modelling studies consistently demonstrate that uncertainty is strongly spatially structured: forecasts are increasingly less certain in areas with sparse surveillance data and more complex ecological drivers than in the western United States. This pattern draws attention to a fundamental problem in infectious disease modelling: risk perception surfaces can be greatly impacted by data availability and reporting intensity. Finer-scale environmental data, improved human case identification, and longitudinal rodent surveillance must all be integrated to increase model adaptability in under-sampled areas.

8. Effects for Public Health and Disease Prevention

8.1. Risk Assessment for Mitigation Planning

Reducing human exposure to infected rodent excrement and restricting opportunities for viral particle aerosol formation are the main components of public health preventative methods for hantavirus infection. In both home and work environments, evidence-based guidelines suggest behavioural safeguards, environmental sanitation, and structural rodent exclusion. Important precautions include keeping clean surroundings that do not draw rodent populations, safely storing food in rodent-proof containers, and closing holes in structures with the proper materials to prevent rodent entry [30].

Activities that could apply contaminated dust should also be avoided or handled carefully. These include cleaning enclosed or poorly ventilated areas, like cabins, sheds, or barns, that have been closed for a long time. When rodent contamination occurs, it is advised to use the appropriate safety equipment to reduce inhalation exposure, prevent dry sweeping or vacuuming, and soak infected areas with disinfectant before cleaning [30]. These guidelines specifically address the main route of transmission found in hantavirus pulmonary syndrome epidemiology and outbreak studies.

8.2. Targeting High-Risk Populations

When communities with elevated exposure risk are identified through epidemiological monitoring and geographic risk modelling, public health interventions are most successful. Hantavirus pulmonary syndrome is persistently more common in geographic hotspots in the western United States, such as the Four Corners region, central Colorado, northern New Mexico, Utah, and portions of Idaho and Washington [4,24].

Exposure risk is mostly determined by social vulnerability in addition to geographic targeting. There may be a disproportionately increased risk of infection and worse clinical outcomes in communities with low housing quality, restricted access to rodent control resources, and inadequate healthcare access [14]. Because they are frequently exposed to rodent habitats and contaminated settings, occupational groups such park rangers, construction and renovation workers, agricultural workers, and wildlife management professionals are also more vulnerable [6,20].

Another significant risk pathway is recreational exposure, especially for hikers, campers, and tourists visiting rural or wilderness regions with rodent populations. During times of increased rodent

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activity or environmental factors that promote rodent population expansion, public health messaging that targets these groups is crucial.

8.3. Surveillance and Early Detection

Continuous surveillance of hantavirus infections, combined with thorough exposure history and geographic data, is critical for refining spatial risk models and enhancing epidemic detection. Predictive risk maps may be updated continuously by integrating epidemiological case data with ecological and environmental datasets, which can guide resource allocation and focused preventative methods [4,25].

These modelling techniques are especially helpful in locating possible risk locations where ecological conditions are favourable for reservoir animals but human cases have not yet been identified. This is crucial because hantavirus infections may go unnoticed in understudied areas or places with poor diagnostic capabilities. Therefore, early detection systems that integrate environmental monitoring with clinical surveillance might enhance readiness and lessen the severity of epidemics through prompt public health responses.

9. Climate Change Implications

9.1. Projected Shifts in Geographic Risk

Climate change is projected to significantly impact the geographic distribution and transmission dynamics of hantaviruses by influencing temperature, precipitation patterns, vegetation productivity, and rodent population ecology. According to projections for the contiguous United States, parts of the northwestern region may see slightly wetter conditions along with ongoing climate change, while the southwestern region is expected to see increasing dryness, more frequent drought conditions, and higher average temperatures over the next few decades [31]. Because mouse population dynamics are extremely sensitive to climate fluctuation, these environmental changes have significant ramifications for hantavirus ecology.

The primary reservoir of the Sin Nombre virus, deer mice (Peromyscus maniculatus), have already shown a strong correlation between precipitation anomalies, increased primary productivity, and subsequent population growth in the southwestern United States due to climate fluctuations linked to El Niño Southern Oscillation (ENSO) events [24,29]. Therefore, unstable ecological conditions that occasionally boost rodent numbers and increase potential for pandemic overflow may result from future climate conditions typified by alternating dryness and episodic rains.

In contrast, many climate scenarios predict higher humidity and precipitation in the eastern United States [31]. The distribution and abundance of alternate reservoir species, like marsh rice rats and cotton rats, may change as a result of these shifting environmental conditions because eastern hantavirus species are linked to wetland and woodland environments. However, current epidemiological data indicates that hantavirus disease will probably continue to be concentrated mainly in western North America, where Sin Nombre virus transmission is more effectively maintained and more strongly linked to the burden of human disease [4].

9.2. Mechanisms of Climate-Driven Change

Numerous interrelated biological and environmental systems moderate variations in hantavirus risk caused by climate change. The impact of temperature and precipitation on mouse population density, survival, breeding success, and food availability is one important pathway. Following periods of high rainfall, increased vegetation growth can provide reservoir species with more food, which can accelerate population growth and increase virus transmission within mouse groups [**?**].

In arid and semi-arid regions of the western United States, prolonged drought and soil degradation may also increase the frequency of dust-producing conditions and dust storms. Because hantavirus is often spread by inhaling aerosolised particles contaminated with mouse excrement, these environmental disturbances may raise the risk of human exposure, particularly in rural and occupational

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settings. Climate-related habitat damage may also drive rats closer to residential and agricultural areas as natural resources become more scarce.

Anticipated warmer temperatures and modest increases in precipitation may facilitate the extension of suitable habitats for reservoir species into higher latitudes and altitudes further north [**?**]. This may increase the risk of hantavirus in historically low-incidence regions of the northern United States and Canada. Future patterns of illness onset may be altered, and public health surveillance efforts may be hampered by such spatial migration of reservoir populations.

The complex connections that climate change is expected to have with ecological, environmental, and human behavioural factors may increase the frequency, severity, and geographic breadth of hantavirus spillover episodes in susceptible locations.

10. Gaps in Knowledge and Future Research Directions

10.1. Outstanding Questions

Despite substantial progress in understanding hantavirus ecology and epidemiology, several key knowledge gaps remain that limit the precision of current risk assessments and predictive models [29].

- **Rodent community dynamics:** The extent to which interspecific interactions among reservoir and non-reservoir rodent species influence hantavirus maintenance, amplification, and spillover risk remains insufficiently understood. Community-level ecological processes may play a critical role in shaping infection prevalence within primary hosts [32].
- **Viral evolution and spatial structure:** The geographic distribution of hantavirus genetic lineages and the extent to which viral evolution is driven by local adaptation to distinct rodent host populations require further investigation, particularly using integrated phylogeographic approaches [33].
- **Transmission thresholds:** Quantitative thresholds in reservoir population density, infection prevalence, and community composition that trigger increased likelihood of human spillover events have not been clearly defined and remain a major gap in predictive modelling [24].
- **Human behavioural and environmental interactions:** The interaction between human behavioural patterns (e.g. occupational exposure, recreational activities, and housing practices) and environmental conditions (e.g. seasonality, land use change, and rodent abundance) is complex and not yet fully parameterised in existing risk models [14].

10.2. Recommended Research Priorities

Future studies should concentrate on incorporating fine-scale environmental, ecological, and epidemiological data to improve the geographical resolution and forecast accuracy of hantavirus risk models [27]. Analyses should specifically consider land-use change and ecotonal (fringe habitat) dynamics, where human–wildlife contacts are most prevalent [14].

Linking epidemiological case data with accurate geolocation of possible exposure areas should also receive more attention, while accepting the limitations of spatial reporting accuracy. More reliable connections between environmental exposure, reservoir populations, and human infection routes might be possible when spatial epidemiology and viral genome sequencing are combined [33].

To better characterise the factors influencing hantavirus spillover risk and guide focused public health interventions, future research should take a multidisciplinary approach that incorporates landscape ecology, molecular epidemiology, and social vulnerability analysis [4,14].

11. Conclusions

In the United States, complex linkages between ecological, environmental, socioeconomic, and climatic conditions favour the spread of the hantavirus from rodent reservoirs to human populations. Hantavirus risk is higher in arid regions with higher rodent richness, social vulnerability, and susceptibility to low levels of development; this risk is higher in the western United States than in the eastern United States. As with other emerging diseases, there is evidence that hantavirus transmission may

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be influenced by fringe habitats.The western United States' high concentration of hantavirus cases is indicative of the convergence of

- Arid climate conditions are favourable to virus persistence in the environment.
- Landscapes transitioning between human development and wildlife habitat
- Rodent communities with multiple potential reservoir species
- Rural populations with limited resources for rodent control and disease prevention
- Recreational and occupational activities that increase human exposure to rodent excrement

To be effective, prevention strategies must address multiple dimensions: focused interventions in high-risk populations and areas, improved housing conditions in rural areas, rodent population management, and public education on exposure avoidance and the safe handling of potentially contaminated materials.

The geographic distribution of hantavirus risk is expected to change as climate change alters precipitation and temperature patterns across North America, potentially affecting low-risk regions. To lessen the threat posed by hantavirus as an emerging infectious disease, studies of reservoir ecology and transmission mechanisms, ongoing surveillance, and flexible public health measures are essential.

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