COMMENTARY

Ecological Complexity and West Nile Virus

Perspectives on Improving Public Health Response

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ABSTRACT

The emergence of West Nile Virus, as well as other emerging diseases, is linked to complex ecosystem processes such as climate change and constitutes an important threat to population health. Traditional public health intervention activities related to vector surveillance and control tend to be reactive and limited in their ability to deal with multiple epidemics and in their consideration of population health determinants. This paper reviews the current status of West Nile Virus in Canada and describes how complex systems and geographical perspectives help to acknowledge the influence of ecosystem processes on population health. It also provides examples of how these perspectives can be integrated into population-based intervention strategies.

MeSH terms: Disease transmission; ecological systems; geographic information systems; systems theory; primary prevention

RÉSUMÉ

L'apparition du virus du Nil occidental, à l'instar d'autres maladies émergentes, résulte de processus écosystémiques complexes, comme le changement climatique, et représente une importante menace pour la santé. Les interventions traditionnelles de santé publique, telles que la surveillance et le contrôle des vecteurs, demeurent limitées dans leur capacité d'endiguer les épidémies ou d'agir sur leurs déterminants. Cet article examine la situation canadienne et l'état actuel des connaissances sur le virus du Nil occidental. En s'appuyant sur une analyse des systèmes complexes et une analyse spatiale, il décrit comment les écosystèmes influencent la santé des populations et, en conséquence, quelles stratégies d'intervention populationnelle pourraient être envisagées.

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West Nile Virus (WNV) as well as other emerging infectious diseases have been characterized as important threats to population health,[1-3] and constitute a major focus of population health intervention and policy research.[4] Fluctuations in climatic variables – most notably temperature, precipitation, humidity and wind – influence the distribution and processes among biological organisms linked to the spatial and dynamic variability of infectious diseases.[5] Disease surveillance and vector control activities must acknowledge the inherent complexity characteristic to ecosystem-based transmission cycles, as well as the complex interactions among the determinants of population health.[6-8] Population-based intervention strategies will require unconventional analytic tools and alternative conceptual foundations if they are to be successful at tackling public health risks characterized by multiple interactions, non-linear rates of change, and spatio-temporal influences. This paper discusses how complex systems and geographical perspectives can contribute to the design of population health interventions for West Nile Virus, and by extension, other emerging infectious diseases.

Transmission and expansion of West Nile Virus

The sudden appearance of severe and fatal encephalitis in dying corvids (i.e., crows, ravens, blue jays) and in humans in New York City in 1999, and in Canada in 2001, provides a compelling example of the expanding range of emerging diseases and a corresponding expansion in diagnostic capacity to detect emerging health threats. West Nile Virus transmission cycles and maintenance mechanisms are usually very complex, and the virus can easily become established if efficient vectors, suitable amplifying hosts, and reliable overwintering mechanisms are available.[9] Indigenous to Africa, Asia, Europe, and Australia, and now North America, the origin of the original strain of WNV is the Middle East, but the mode of introduction is unknown.[10] Humans are incidental (dead end) hosts since they can become ill as a result of the virus, but do not develop viremia that is required for the continuation of the transmission cycle if bitten by another mosquito.[11]

West Nile Virus constitutes a serious threat to human population health and well-being. Annual human case incidence now ranks WNV second only to LaCrosse encephalitis virus as the leading cause of reported human arboviral encephalitis in the United States.[11,12] The 2002 WNV epidemic in the United States was the largest arboviral epidemic documented in the western hemisphere, with the greatest intensity in the central states and Great Lakes region amounting to a total of 3,389 human cases across 2,289 counties in 44 states.[13] In 2002, Health Canada documented WNV activity in five provinces (Manitoba, Nova Scotia, Ontario, Quebec, and Saskatchewan) with 343 cases reported for Ontario.[14] However, doctors with the Canadian Infectious Disease Society suspect nearly 1,000 symptomatic human cases of WNV in Ontario in 2002, much larger than the official reports.[15] West Nile Virus may also be transmitted indirectly by blood and blood product transfusion and organ transplantation,[16] directly via parenteral transmission from breastfeeding,[17] as well as occupationally among medical laboratory workers through percutaneous injection.[18]

TABLE I
Definitions* of Key Terms

Term	Definition
Complex Systems	There is no one accepted definition of complex systems. However, the properties of a complex system are: openness (to material and energy flows), nonequilibrium (exist in states away from equilibrium), non-linear (behave as a whole and not amenable to reductionist approaches), self-organizing (non-Newtonian, characterized by feedback loops and surprise), hierarchical (systems within systems at different scales), catastrophic behaviour (normal but could involve thresholds), chaos (prediction always limited no matter how powerful our models or computers). In short it means irreducible uncertainty.
Attractors	Dynamic complex systems are inherently chaotic and unstable, but they usually settle down into one of a number of possible steady states. These steady states are called attractors. Steady systems are usually found near attractors due to feedback loops.
Dissipative Structure	A system that becomes more differentiated requires more energy to sustain it than the simpler system it replaces, and becomes less efficient in the use of energy.
Leverage points†	There are levers, or places within a complex system (such as a firm, a city, an economy, a living being, an ecosystem), where a small shift in one thing can produce big changes in everything.
Emergence	When a system is able to change profoundly and generates new properties and structures from existing ones, it is said to have emergent properties. The new system is qualitatively different and did not result from traditional Newtonian mechanics, but rather from simple non-linear interactions.

* An excellent introduction to complex adaptive systems and ecosystem approaches can be found on the personal website of Dr. James Kay at www.jameskay.ca
† Look for the Winter 1997 essay entitled "Places to Intervene in a System" by Donella Meadows at www.wholeearthmag.com

A complex systems perspective

A complex systems perspective recognizes that fundamental ecosystem (physical, biological and social) processes affect the survival and reproduction of all living organisms.[19] A long history of coevolution has governed the relationship among vectors, microorganisms (viruses for example), their hosts, and the environmental conditions within which they interact.[20] Even with such history, the diversity, distribution, and effects of infectious diseases are in constant flux. For example, ecosystem processes such as interactions between vectors and hosts are inherently complex since each element may adapt and/or reorganize in response to intervention. Enhancing infectious disease surveillance and integrated vector control will require acknowledgement of the complexity underlying ecologically-linked transmission cycles.[21]

Complexity in any ecosystem arises from inter- and intra-specific interactions among individuals, interactions across levels of organization, and the interaction of organisms with the environment over space and time.[22] Complex systems theory incorporates notions of adaptation[23] and emergence,[24] and has been adopted by the Centers for Disease Control's Syndemic Prevention Network to examine the synergisms and interactions evident in the connections between higher-order, health-influencing phenomena.[25] Complex systems consist of dissipative structures and attractors. Dissipative structures and processes describe the state of any system from a position far from equilibrium to one that is close to equilibrium.[26] Tornados or autocatalytic chemical reactions are good examples. Attractors are specific points or features within a system that exert leverage on future evolution.[27,28] (See Table I for definitions of specialized terms used in this paper.)

Figure 1 represents graphically an application of complex systems thinking adapted to understanding the emergence of WNV in relation to human activities. The model proposes four states: exploitation and rapid growth, conservation, release (collapse), and reorganization, as well as a list of potential attractors likely to be found at each state. By following the figure eight pathway in the direction of the arrows, it is possible to trace the relationships between human-focussed development activities and resulting reductions in system resilience leading to the emergence of infectious disease and possible public health responses. Emergent properties may also be positive by promoting dynamic interaction between different attractors within the system. For example, the creation of intersectoral and cross-jurisdictional linkages among traditionally disparate groups, such as provincial health authorities and federal wildlife research agencies, reveals efforts to understand the dynamic nature of human-ecosystem interactions that foster the conditions necessary for opportunistic viruses.[29] Typical population-based interventions are adaptive and generally located in the pathway between the system states of *release* and *reorganization*, a position where the system is unstable and behaving chaotically. Intervention in complex environments should take place at multiple points along the pathway between system states, even though intervention targets may be difficult to identify. Adopting a systems perspective is useful for identifying those attractors and structures more or less amenable to change, but does not guarantee successful intervention.

Geographic perspectives on infectious disease and intervention

Patterns of differentiation in complex systems have a spatial dimension that is characterized by patterns of territoriality and spatial heterogeneity. Incorporating geographical perspectives into population-based intervention strategies forces researchers to contemplate location and place, as well as the relationship between disease and population health patterns

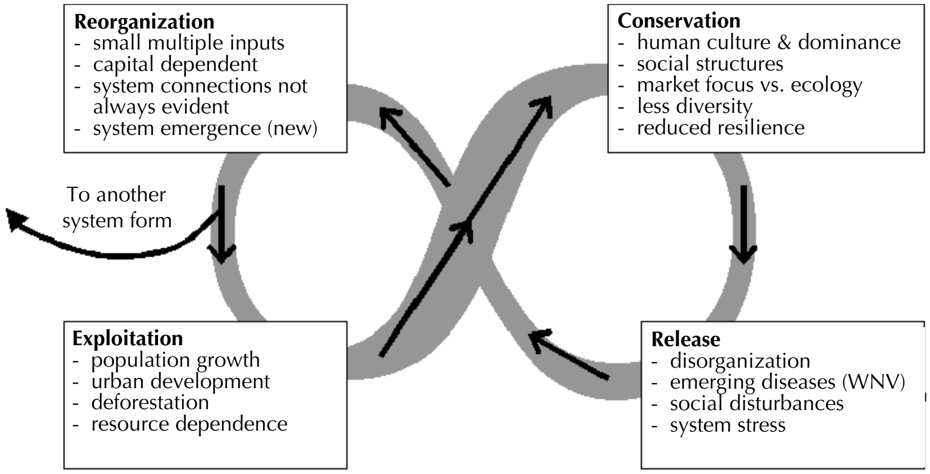

Figure 1. The emergence of West Nile Virus from a complex systems perspective. Follow the figure eight pathway in the direction of the arrows to trace the relationships between human-focussed development activities and resulting reductions in system resilience leading to the emergence of infectious disease. Intervention activities should take place at multiple points along the path and not only after the **release** state (point where WNV becomes a public health threat). Figure is a modification of Hollings' Four Box Model.

across scales and social groups. For example, the social, cultural and physical environment exacts a "nested" effect on the health of populations: features of the micro-, meso- and macro-environmental scale interact to create health in context.[30]

Understanding the spatial dynamics of West Nile Virus is critical for the determination of its emergence in new locations or among potential vectors and hosts. Often the emergence of infectious disease is characterized by complexity and chaotic processes. For example, the leading edge of many infectious disease epidemics is often jagged and irregularly shaped, reflecting spatial variation in the distribution of susceptible hosts, variation in localized contact rates, long distance vector migration patterns, or variations in intervention intensity and duration (e.g., intervention activities tend to vary considerably among health units).[21] Analyses of pathogen dispersal characteristics display distinct fractal patterning inherent to non-linear processes.[31] Fractal models have been proposed to explore the spatial shape of social networks in the process of HIV transmission.[32]

Effective health intervention approaches tend to be collaborative and multi-level in nature.[33,34] Implementation of multi-level interventions increases the amount of complexity creating challenges for finding established measures for variables across scales and for intervention evaluations. These challenges can be overcome by employing multi-level models using geographical aggregations of space,[35] or by assessment of patterning of emerging disease at distinct levels of aggregation.[36] Spatial patterning assessments have been used to analyze the spatial distribution of mosquito bites on the human body.[37] Such information would be useful for tailoring intervention strategies to reduce personal exposures. Spatial approaches have also been used to assess the relationship between intervention coverage and public health unit areas. It is highly unlikely that spatial patterning of disease vectors or locations of transmission hotspot areas will fit nicely into existing public health unit boundaries that are artificially determined from political/administrative processes or data collection regimes.[38] Adoption of a spatialized ontology into the design of intervention for West Nile Virus may well enable the development of surveillance and control strategies based on meaningful biological or ecologically relevant units across multiple scales and ecosystem processes.

The concept of location is critical to understanding the intersection of population health determinants and ecologically-relevant intervention activities.[39] Mostly absent from the population health discourse is discussion about the role of geomatics as a common conceptual framework for studying the location of health aetiology and intervention. Geomatics comprises a multi-disciplinary approach to the science and technology associated with gathering, storing, analyzing, interpreting, modeling and distribution of geo-referenced information.[40] A major strength of using geomatics for population-based intervention is the ability to collect and merge large amounts of varied data into a single database. For example, by using a geomatics framework, it would be possible to overlay and integrate multiple data sets from various scales to describe health status, examine interactions among health determinants, and help target intervention strategies. Such data may include, but are not limited to: population data (e.g., socio-economic, census information), environmental and ecological data (e.g., pollution, vegetation, remotely sensed information), topography, hydrology and climate data (particularly useful for understanding vector-borne disease), land-use and public infrastructure information (e.g., schools, drinking water supplies), transportation networks, health infrastructure and epidemiologic data, and most any other data.[41] Successful interventions oriented towards the reduction of risk from malaria in Africa have adopted a geomatics approach to assess the type and severity of malaria transmission, and to tailor appropriate control measures according to the capacity and needs of specific regions.[42] Although many public health ministries and units in Canada use geographic methods for infectious disease control, it is not clear whether these methods extend much beyond visual display of the data or if geographic thinking extends to the actual design of health interventions.

CONCLUSIONS

West Nile Virus is now endemic in Canada and constitutes a serious concern for population health and well-being. Although the number of confirmed vector-borne cases is small, many of these cases go unreported. Transmission cycles are connected to local and global climate variability and complex ecosystem dynamics. A complex systems approach is useful for thinking about population-based intervention to WNV because: 1) it acknowledges relationships between ecosystem-level interactions and the emergence of infectious disease, and 2) it helps to identify structures and processes that are more or less agreeable to change at multiple points and scales within a system. Geographical perspectives also have great utility in the design of intervention strategies. Gaining insight into the spatial processes influencing the spread of West Nile Virus will ultimately aid in the design of more efficient surveillance and monitoring activities. Many vector-borne and other emerging infectious diseases exhibit a spatial patterning or clustering which may vary according to the scale under investigation. Interventions can use location-specific information to modify intervention planning by maximizing resources for regions with severe outbreaks, and to incorporate traditionally disparate information and data relevant to infectious disease control activities. Ideally, public health workers, physicians, and other health care providers might benefit from the adoption of these perspectives into infectious disease intervention planning and may be made more aware of the relationships among ecosystem-level processes, human activities, and the population health risks associated with West Nile Virus.

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