Studying Disease Dynamics Using a Network Model

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Abstract:

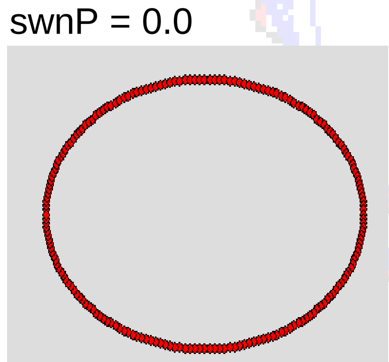
Globalization increases the likelihood that disease agents spread more quickly and reach a larger number of hosts. Recent research suggests that small-world networks are a more realistic representation of human social interactions than random or regular networks. We create small-world networks by starting with a circulant and rewiring each edge randomly with a probability swnP (a parameter setting of our model). Our model explores vaccinating random nodes, nodes with the highest degrees (hubs), nodes with the lowest clustering coefficients, nodes with the highest clustering coefficients and nodes contained in cross-cut edges on regular, small-world, and random networks. We also investigate how k (the original degree of each host) and NCR, (Neighbor Contact Rate or the probability that influenza will spread from one neighbor to another each day of the infectious period) change the dynamics of disease spread. We have found that an increase in k or an increase in NCR both increase the proportion of the population becoming infected and there is a significant interaction between these two terms.

Methods:

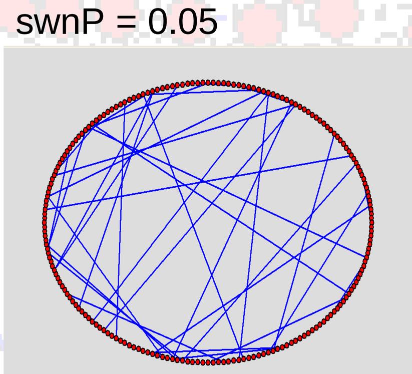
The model:
We used an agent-based model to simulate the progress of an outbreak of influenza through a network of hosts. The network structure ranged from regular to random following Watts and Strogatz (1998). We began with a k-regular circulant containing 1,000 or 10,000 hosts connected to their 0.5k closest neighbors on each side. We used k values ranging from 2 to 32. Each edge was then rewired to a new, randomly chosen host with probability swnP. This allowed us to create networks ranging from regular (swnP = 0) to random (swnP = 1). We initially infect one host and each day of the infectious period, each neighbor of the infectious host had a set probability (NCR, or Neighbor Contact Rate) that it would contract influenza. We set this probability at values varying from 0 to 1.0.

Networks:

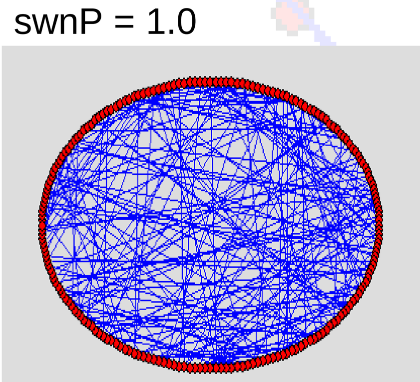
swnP = 0.0



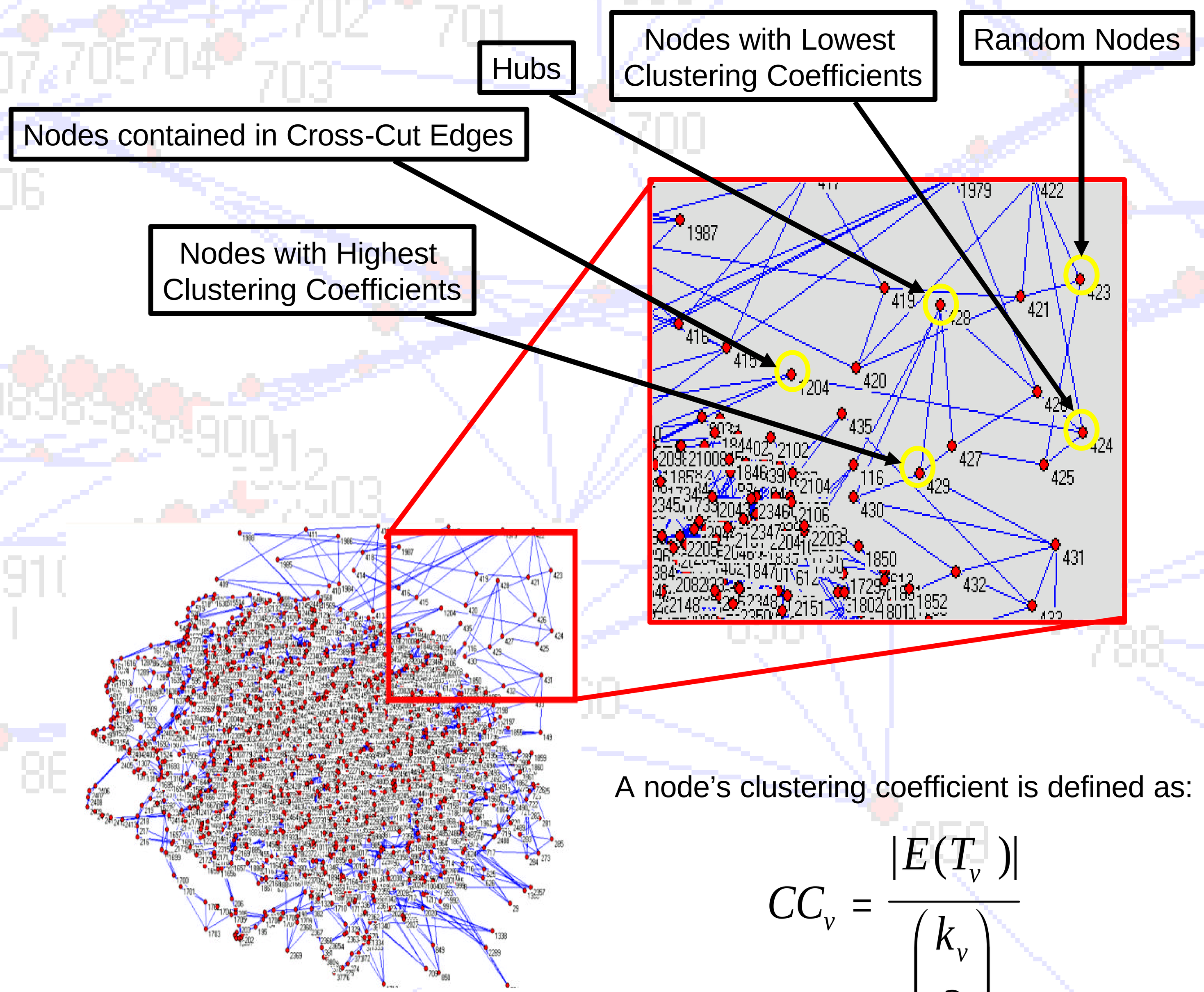
swnP = 0.05



swnP = 1.0



Simulations:
During our simulations, a proportion of the population, ranging from 0% to 30%, was vaccinated with attenuated influenza. Vaccination strategies included vaccinating:

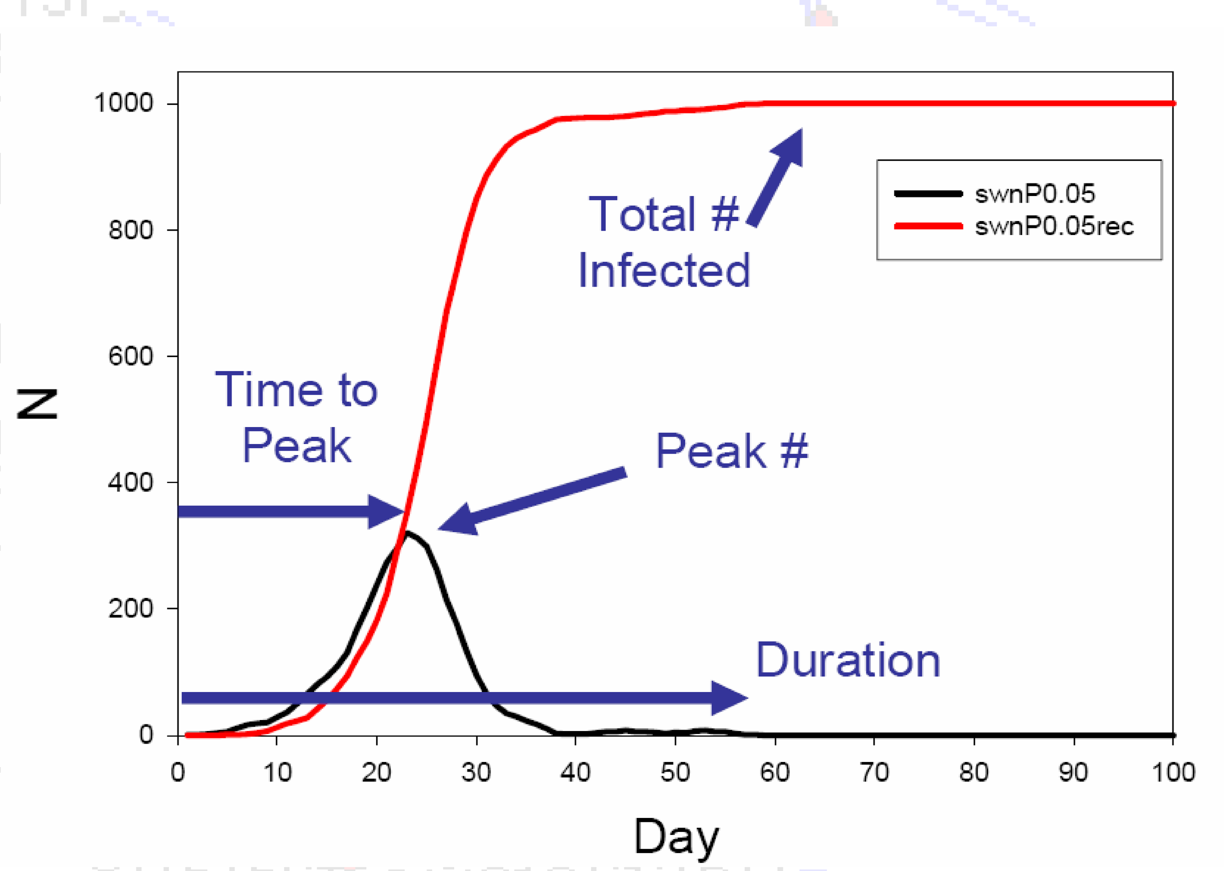


A node's clustering coefficient is defined as:

$$CC_v = \frac{|E(T_v)|}{\binom{k_v}{2}}$$

Analysis:
We ran each simulation until there were no infectious hosts left (fewer than 1,000 simulated days). We tested the effects of NCR, k, vaccination strategy, swnP, and population size on the proportion of the population infected by influenza. We also tested the interactive effects of NCR and k on the proportion of the population infected by influenza. We did these tests using ANOVA (Minitab, version 14). Contrasts were conducted using Tukey's test.

Disease Dynamics:



Results:

Figure 1. The percent of the population infected with influenza differed for different vaccination strategies. Bars with different letters were significantly different.

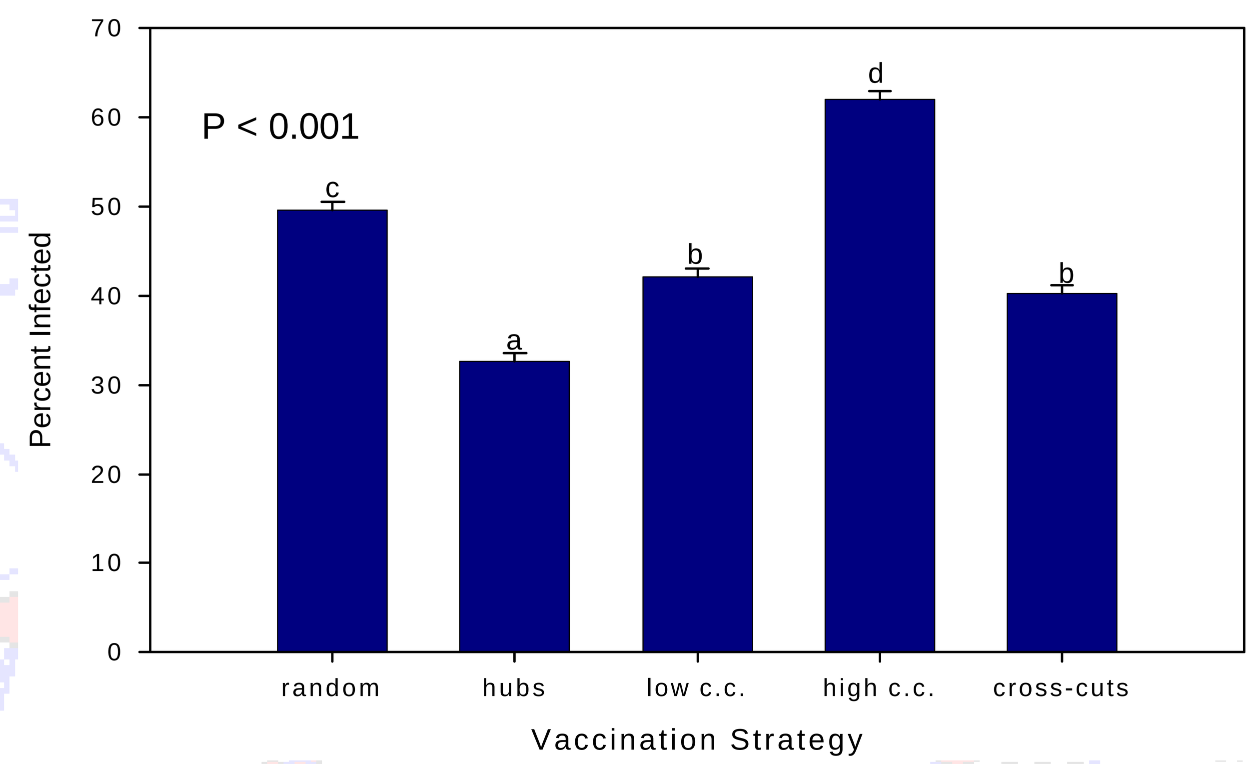


Figure 2. NCR and k explain a higher percentage of the variance of this analysis than swnP and population size. The four main effects were highly significant (P < 0.001).

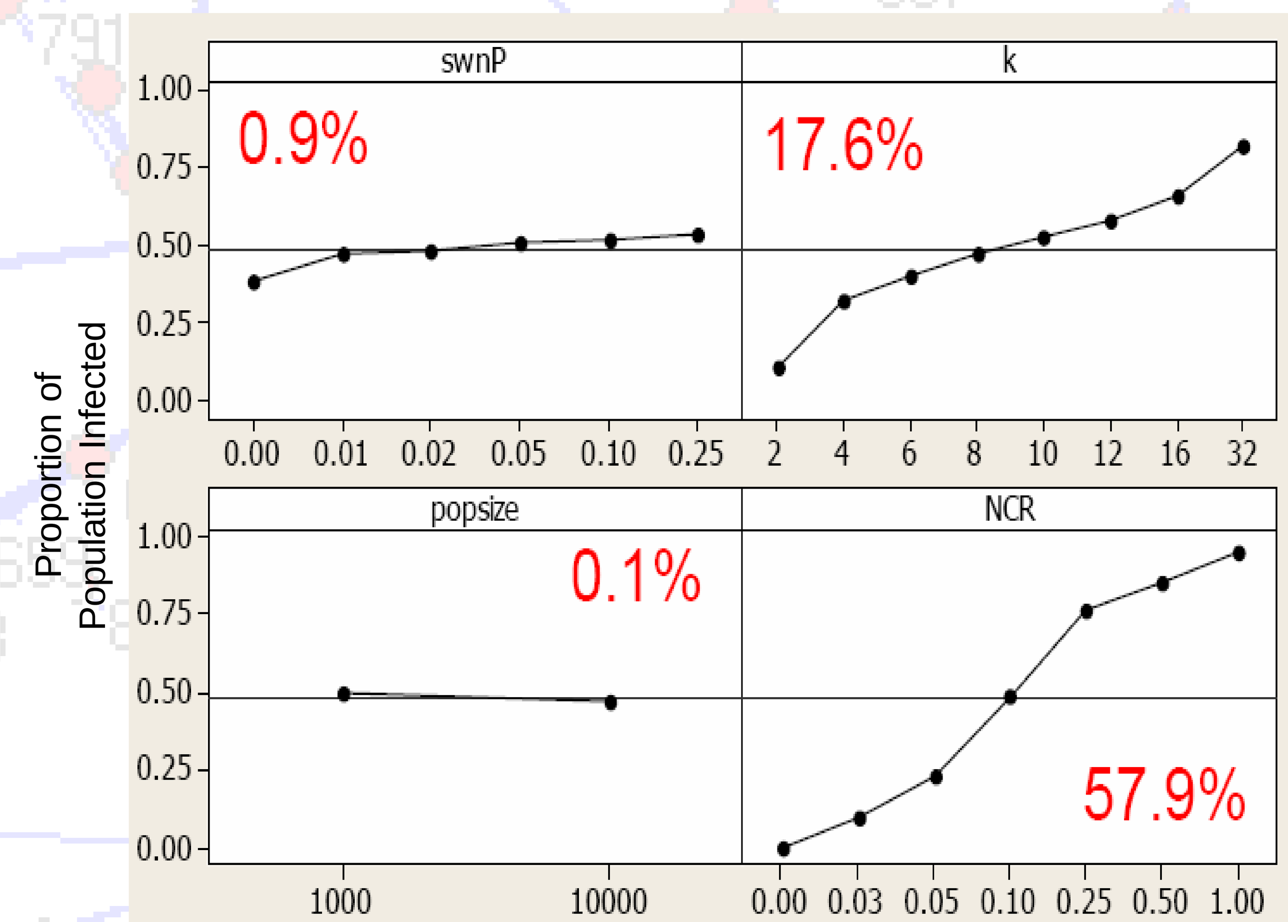
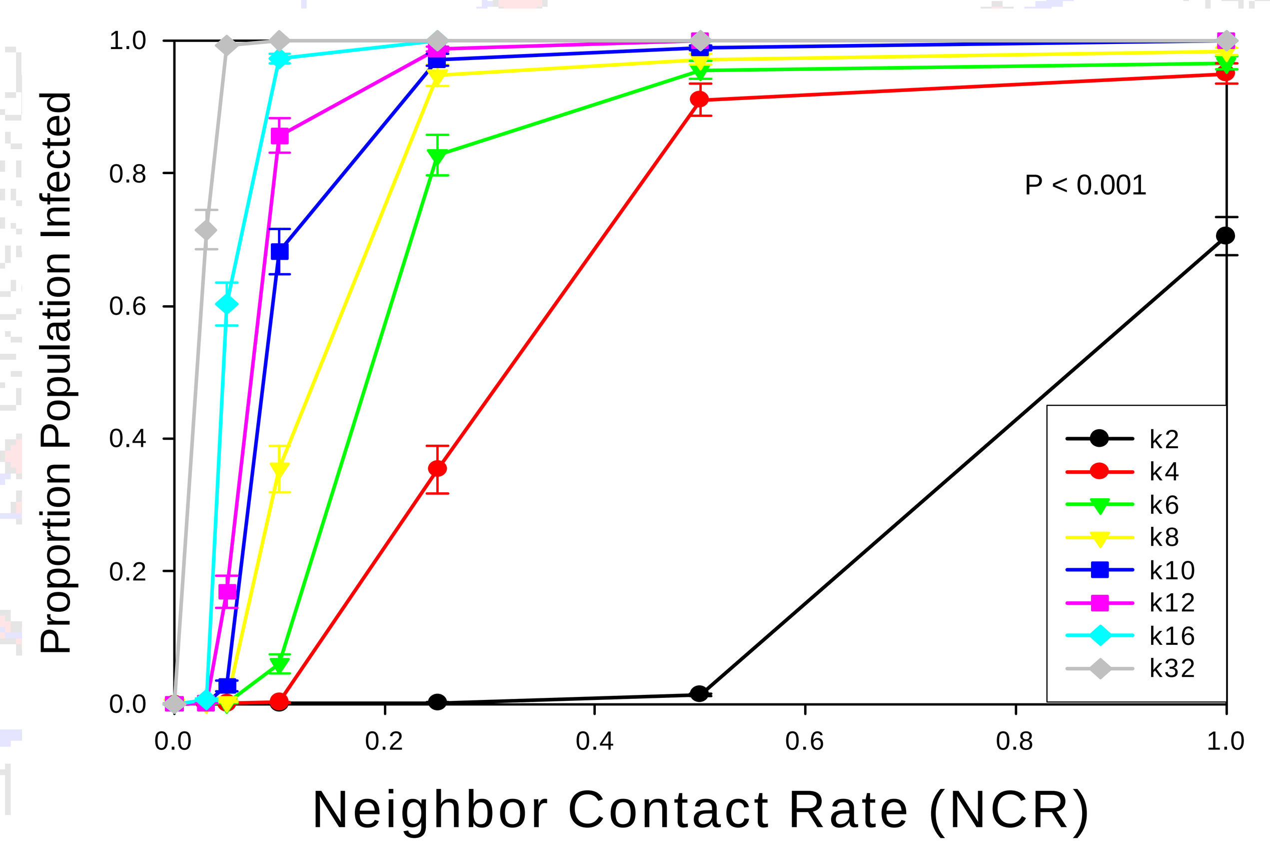


Figure 3. There is a significant interaction between k and NCR. We found that if the original degree of each host is low, a high NCR is required for a high proportion of the population to become infected. If the original degree of each host is high, a lower NCR results in a high proportion of the population becoming infected.



Conclusions:

Our data suggest:

- Targeted vaccination strategies including vaccination of hubs, nodes contained in cross-cut edges, and nodes with lowest clustering coefficients result in a lower percentage of the population becoming infected than vaccinating randomly and vaccinating nodes with the highest clustering coefficients.
- As the Neighbor Contact Rate (NCR) increases from 0 to 1.0, a higher percentage of the population becomes infected.
- As the original degree of each host (k) increases from 2 to 32, a higher percentage of the population becomes infected.
- k and NCR are more important in influencing the proportion of the population infected than swnP and population size.
- k and NCR interact to affect the proportion of the population that becomes infected.

References:

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