Variation in thermal pressures and resource availability drives disease dyanmics

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Introduction

- Direct transmission of infectious disease is driven largely by physical proximity between infected hosts and susceptible hosts.
- Physical proximity can be driven by complex social dynamics, but in a simplified framework is most easily described by the probability that organisms making foraging choices on a landscape chose the same patch and then subsequently a transmission event occurs
- Foraging choices on a landscape is driven largely by resource availability
- In an environment where organisms are sensitive to the thermal landscape as well, choices will be made not just based on resource availability but on the thermal suitability of various patches
- A simplified landscape can therefore be thought of as jointly described by the thermal and resource properties of a given patch
- Transmission dynamics on a landscape will therefore be characterized by these factors as well
- In this simplified framework then, the probability of a single infected individual transmitting a generalized pathogen to another individual is modulated by the thermal and resource landscapes
- A biological motivation of this is to consider some burrowing organisms which directly transmit a pathogen of interest between them, dependent on physical proximity

Methods & Results

To abstract the transmission dynamics sufficiently, we imagine a landscape where a series of individuals make daily landscape-level selections on where they will forage, with no memory and perfect knowledge of the landscape. Therefore, they chose from the available cells, w_i based on each cell's value as a probability. Since these are probabilities it must be true that

$$\sum_i w_i = 1. \tag{1}$$

If there are S susceptible individuals in the population that assort randomly across space according to the probabilities w_i and $I = 1$ infected individual, we want to know the probability that the disease will spread. From a purely contact perspective, this is given by the probability that the infected individual occupies a location that also has at least one susceptible individual.

A. Co-location and transmission

Assuming a population consisting of $S > 0, I > 0$, transmission requires at least the co-location of one of each group. We can consider both co-location and transmission.

A.1. Determining the probability that at least one S is located in a cell i. The probability that patch i has zero susceptible individuals is $P(S_i = 0) = (1 - w_i)^S$, where S is the number of susceptible individuals on the landscape. Thus, the probability that at least one patch at location i has at least one susceptible individual is given by:

$$P(s_i \geq 1) = 1 - P(s_i = 0) \tag{2}$$
$$= P(s_i = 1) + P(s_i = 2) + P(s_i = 3) + ... + P(s_i = S) \tag{3}$$

Each of the terms above can be expanded as follows:

$$P(s_i = k) = \binom{S}{k} w_i^k (1 - w_i)^{S-k} \tag{4}$$

and therefore

$$P(s_i \geq 1) = \sum_{k=1}^{S} \binom{S}{k} w_i^k (1 - w_i)^{S-k} \tag{5}$$
$$= \left((1 - w_i)^{-S} - 1\right)(1 - w_i)^S \tag{6}$$
$$= 1 - (1 - w_i)^S \tag{7}$$

A.2. Joint Probability for Co-location of S and I. For disease spread to occur, both a susceptible individual and an infected individual must be in the same cell. The probability of this is the product of the independent events:

$$P(\text{collocation in cell } i) = P(S_i \geq 1) \cdot P(I_i \geq 1). \tag{8}$$

Expanding this:

$$P(\text{collocation in cell } i) = \left[1 - (1 - w_i)^S\right] \cdot \left[1 - (1 - w_i)^I\right]. \tag{9}$$

B. Landscape with a known distribution

In above formulations, the landscape values w are a function of both T and R, however, we can make a further simplifying assumption in some cases that the values, while implicitly still based on T and R are instead given by some known distribution. The landscape on which individuals are making occupancy decisions can be thought of as consisting of normalized values, where the number of patches n is sufficiently large. We also focus on the case where there is only one I individual and transmission is assured by co-occurring on the landscape.

We begin considering that w takes a uniform random distribution. We assume that the quality q_i of each patch is drawn at random from a uniform distribution $(0, 1)$, and then transform these qualities to get patch weights w_i by dividing each patch by the total of the quality values where $i = 1, ..., n$.

$$w_i = \frac{q_i}{\sum_i q_i} \tag{10}$$

Here, w_i are therefore nearly uniformly distributed

$$(0, \frac{2}{n}) \tag{11}$$

for large enough n. Here we are considering the case where co-location by two S individuals is given by

$$n * w(1-(1-w)^S). \tag{12}$$

If we assume that $n > 2$ and also that $S \geq 1$, then the expectation of our co-location is:

$$E[n * w(1-(1-w)^S)] = \frac{n^{-S}\left(\left(2(S+1)(S+2)-n^2\right)n^S + (n-2)^{S+1}(n+2S+2)\right)}{2(S+1)(S+2)}. \tag{13}$$

If we

We could also assume that the weights are exponentially distributed, since n random draws from an exponential with a mean $\frac{1}{\lambda} = 1$ would sum to a mean of 1, given large enough n. That would take the form

$$E[n * w(1-(1-w)^S)] = \frac{1-n^2+S-\rceil^{-n}(-n)^{-S}(1+n+S)((-1+(-1)^{2S}\Gamma(2+S)+\Gamma(2+S,-n)}{1+S} \tag{14}$$

B.1. Probability of Successful Transmission. To determine whether or not transmission can occur, we consider the case where infected and susceptible individuals are present on the same landscape patch, and also the likelihood of a transmission event occurring successfully. We denote this as $\epsilon(T)$ which is the temperature dependent probability of transmission. Given some collocation, if there is some patch with $S = 1, I = 1$, the likelihood of transmission is just $\varepsilon_i(T)$. In the case of $S = 2$, we have the probability of

$$\text{At least one S getting infected} \rightarrow 1-(1-\varepsilon(T))^2, \tag{15}$$

$$\text{Both } S \text{ getting infected} \rightarrow \varepsilon(T)^2, \text{and} \tag{16}$$

$$\text{Neither } S \text{ getting infected} \rightarrow (1-\varepsilon(T))^2 \tag{17}$$

B.2. Some k number of susceptible individual and one infected. If there is only $I = 1$ then the probability of at least one of the susceptible k undergoing infection, $P^*(S, I)$ is

$$P^*(k, I=1) = \sum_{k=1}^{k=S} \binom{S}{k} w(T)^{k-1}(1-w(T))^{S-k}(1-(1-\varepsilon(T))^k) \tag{18}$$

From there, we can understand that the probability of a disease spreading on the landscape from cell i, $\phi_i(k, I=1)$ is

$$\phi_i(k, I=1) = 1-(1-w(T)\varepsilon(T))^S \tag{19}$$

And therefore the probability of it spreading on the landscape at all is:

$$\boldsymbol{\phi}(k, I=1) = \sum_i 1-(1-w(T)\varepsilon(T))^S \tag{20}$$

$$w_i = \text{Max}(0, f(T_i, R_i)) \tag{21}$$

where $f(T_i, R_i)$ is the function defining the suitability of patch i based on the resource availability and temperature suitability of patch i:

$$f(T_i, R_i) = \frac{I_{\text{max}}(T_i R_i)}{R_i + R_{\text{half}}} - m(T_i), \tag{22}$$

with $m(T)$ being a respiration term of the organism, and $I_{\text{max}(T)}$ is the maximum uptake rate, where $m(T) = m_a e^{m_b \times T} + m_c$ and $I_{\text{max}}(T) = e^{-(T-T_I)^2/\gamma}$ with m being an approximated exponential version of the Boltzmann-Arrhenius relationship. Here T_I is the optimal temperature value and γ determines the breadth of the response. This value is dependent on each cell, where T_i is the temperature value at i and R_i is the inflow supply of some resource for the organism choosing it's location **??**. The values for a given cell of T and S are drawn from:

Bibliography

Supplementary Information

Figures/temp.png

Figure S1. This is an endosome.
(**A**) This is a supplementary figure shown as a two-column image with a legend underneath.

Supplementary Videos

Figures/temp.png

Figure SV1. This is a video of a lysosome.
A typical caption would go here. We use a thumbnail version of the video file as the figure.
Time, seconds. Scale bar, 10 µm.

Supplementary Tables

Movie	US Release Date	Director	Screenwriter(s)	Story by	Producer
Episode IV – A New Hope	May 25, 1977		George Lucas		Gary Kurtz
Episode V – The Empire Strikes Back	May 21, 1980	Irvin Kershner	Leigh Brackett and Lawrence Kasdan	George Lucas	Gary Kurtz
Episode VI – Return of the Jedi	May 25, 1983	Richard Marquand	Lawrence Kasdan and George Lucas	George Lucas	Howard Kazanjian

Table S1. Original "Star Wars" Trilogy
Extracted from https://en.wikipedia.org/wiki/List_of_Star_Wars_films.