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 $i = 1, ..., n$.

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

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figs/si/constant-uniform.pdf
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60 Here, w_i are therefore nearly uniformly distributed

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

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

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

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

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

63 If we compare this set of expected values, varying the ratio of S/n, then we can see our expected values match the
64 draws from a simulated distribution
65 We could also assume that the weights are exponentially distributed, since n random draws from an exponential with
66 a mean $\frac{1}{\lambda} = 1$ would sum to a mean of 1, given large enough n. That would take the form

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

67 **B.1. Probability of Successful Transmission.** To determine whether or not transmission can occur, we consider the
68 case where infected and susceptible individuals are present on the same landscape patch, and also the likelihood of
69 a transmission event occurring successfully. We denote this as $\epsilon(T)$ which is the temperature dependent probability
70 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:

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

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

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:

84 **Bibliography**

Supplementary Information

Figure S1. This is an endosome.

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

Supplementary Videos

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.