

# Coupled models of structured contagion processes in human-environment systems

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# First Project

# Background

- Population beliefs about the usage of non-pharmaceutical interventions (NPIs) can have a major effective on the epidemic landscape
- Population age distribution is a key factor in both NPI usage and COVID-19 mortality
- Vaccine rollout important to reducing mortality in the long term  
Bubar et al., 2020; Buckner, Chowell, and Springborn, 2020

## Outline of project

- ① Describe age-structured compartmental model of COVID-19 infection in a population, coupled to model of social distancing dynamics.
- ② Fit model to data from Ontario, Canada
- ③ Evaluate outcomes from different vaccination strategies, comparing vaccination of vulnerable populations vs vaccination of susceptible populations

# Compartmental model overview

## Disease Compartments

$S_i(t)$  : Susceptible

$S_{2,i}(t)$  : Vaccinated but still susceptible

$V_i(t)$  : Vaccinated and immune

$E_i(t)$  : Exposed

$P_i(t)$  : Pre-symptomatic

$I_{a,i}(T)$  : Infectious and asymptomatic

$I_{s,i}(t)$  : Infectious and symptomatic

$R_i(t)$  : Recovered

where  $i = 1 \dots 16$  comprises age structure

## Social compartments

$x(t)$  : Uses NPIs

$-x(t)$  : Does not use NPIs

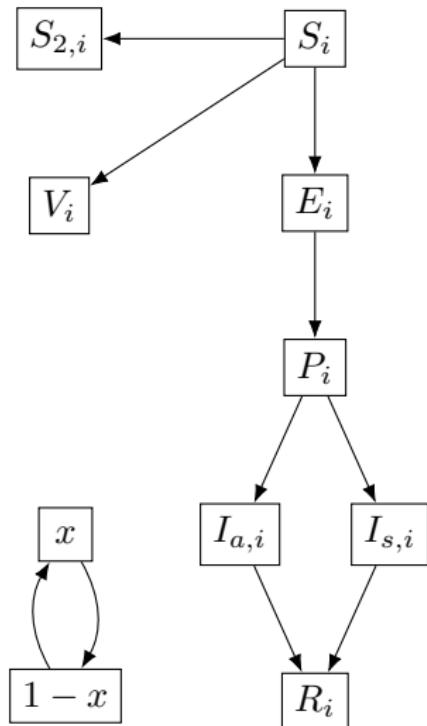


Figure: Compartments

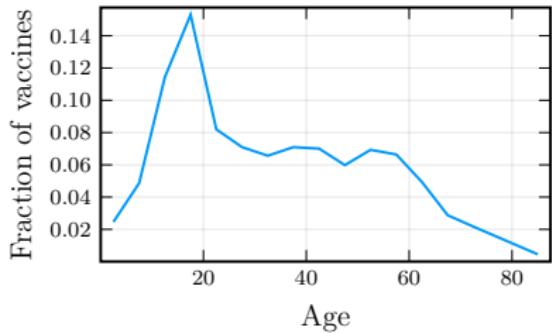
# Vaccination strategies

We compare four vaccination strategies

- $> 60$  first
- $< 20$  first
- Uniform
- Contact-based

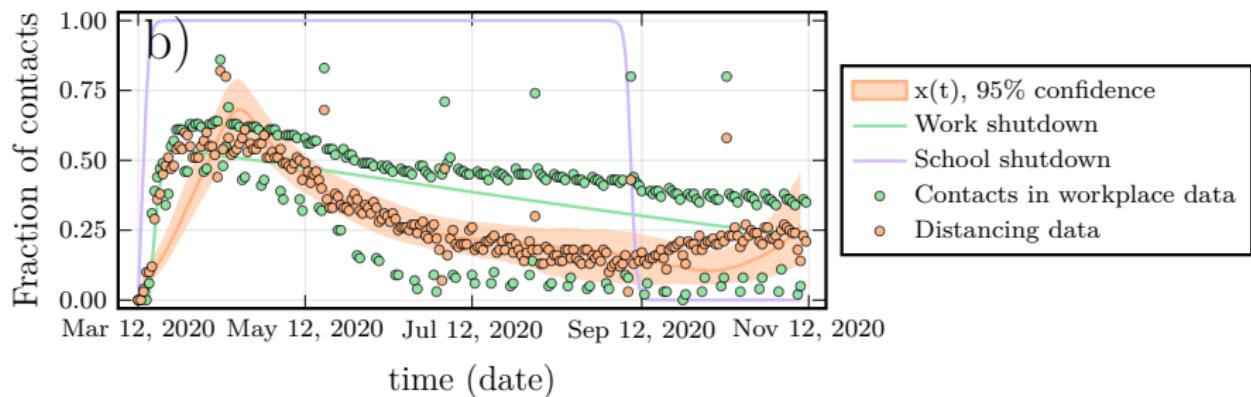
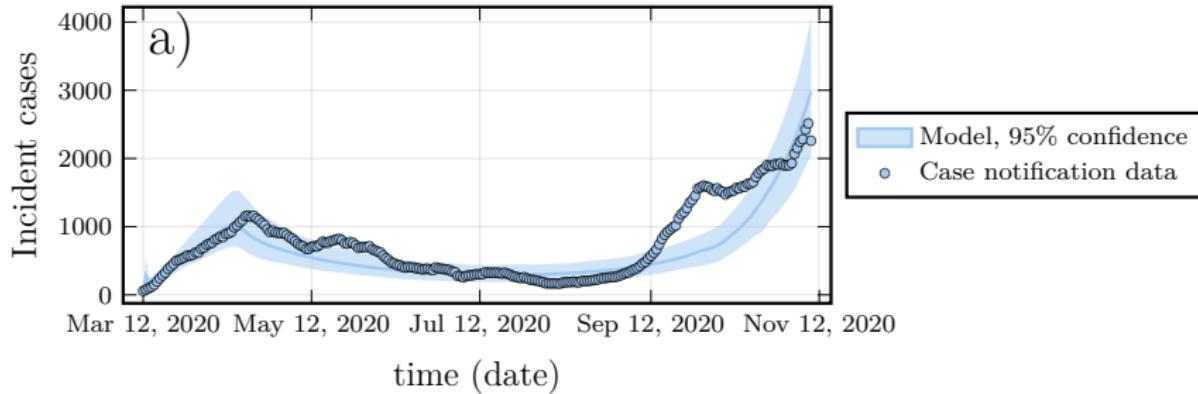
with respect to reduction in cumulative mortality after 5 years.

Contact-based vaccination strategy

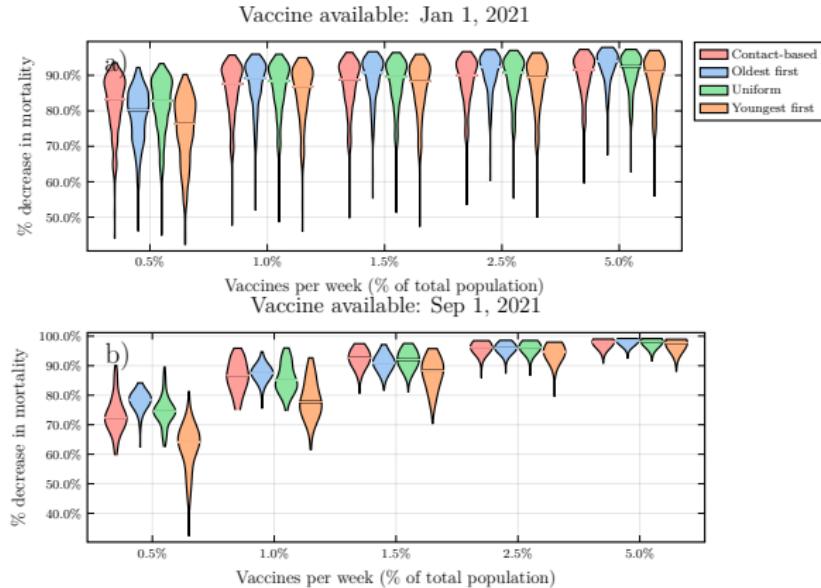


**Figure:** The contact-based strategy is the normalized leading eigenvector of the sum of the contact matrices

# Parameterization

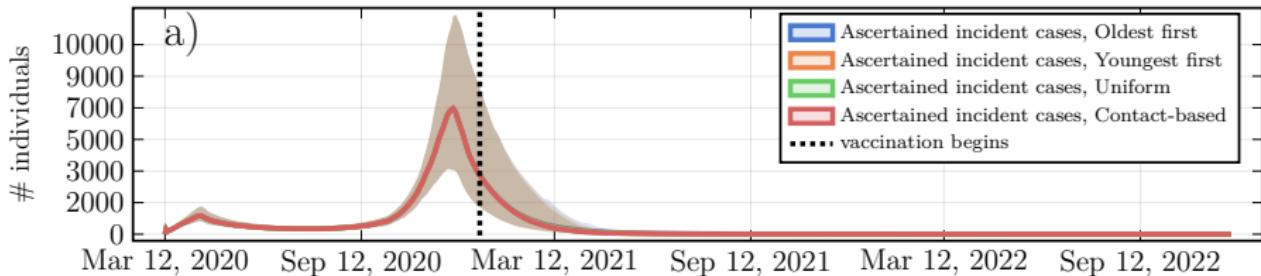


# Results

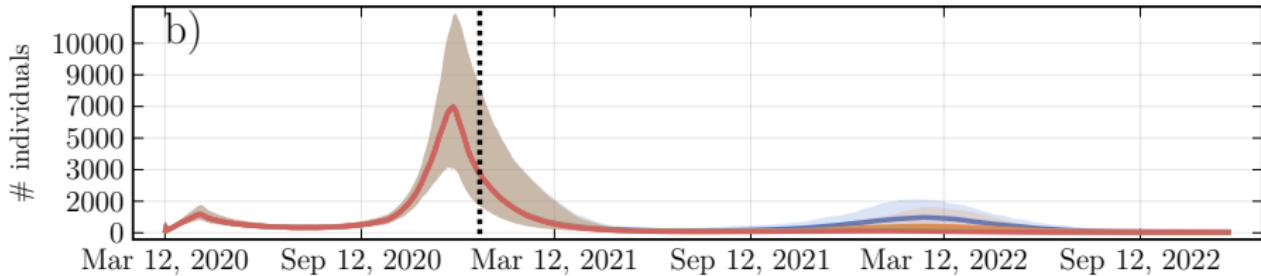


**Figure:** Percentage reduction in cumulative mortality due to COVID-19 after 5 years with respect to  $\psi_i$ , expressed as a percentage of the total population per week. Here  $v_{D_i} = v_{T_i} = 0.75$ , shutdown at 200% of first wave. Percentage reductions are relative to no vaccination.

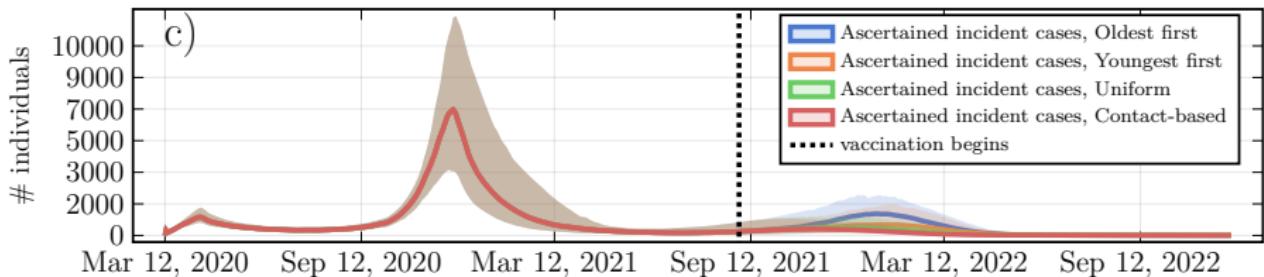
Vaccination begins on Jan 1, 21, 1.5% of pop. vaccinated per week



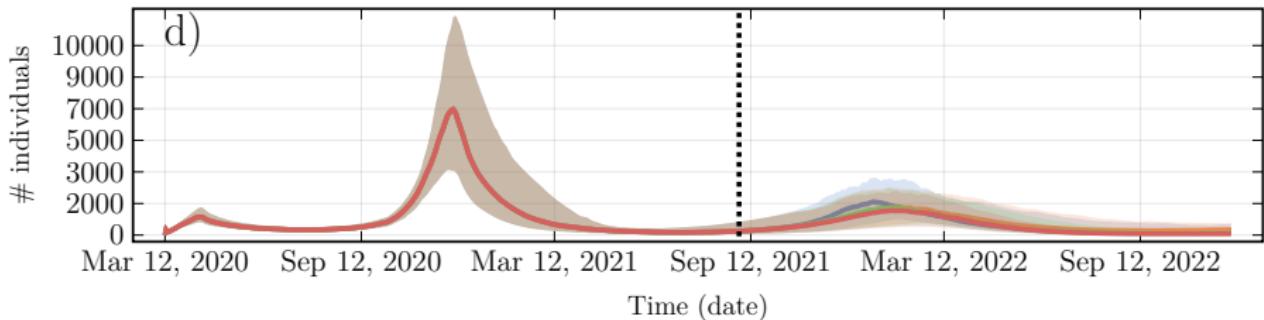
Vaccination begins on Jan 1, 21, 0.5% of pop. vaccinated per week



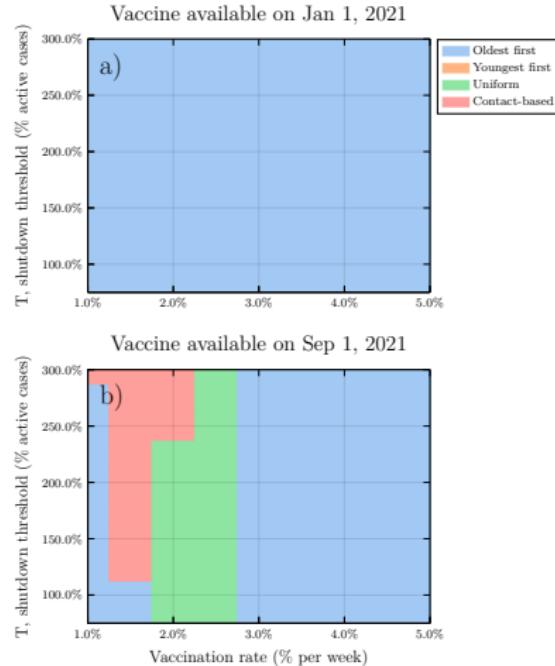
Vaccination begins on Sep 1, 21, 1.5% of pop. vaccinated per week



Vaccination begins on Sep 1, 21, 0.5% of pop. vaccinated per week



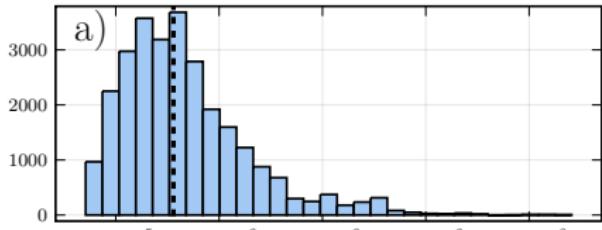
# Results



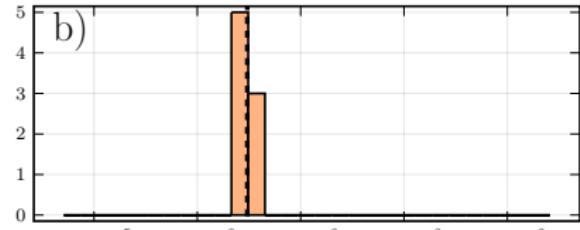
**Figure:** Each parameter pair is colored according to the strategy that prevents most deaths on average, over all realizations of the model.

# Results

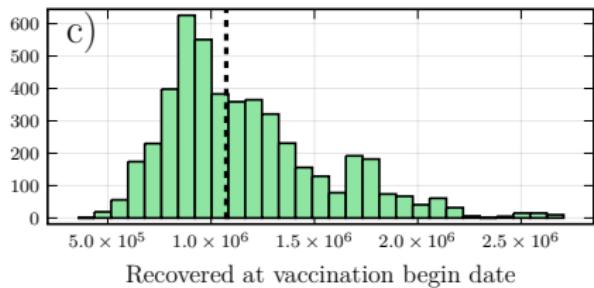
Oldest first



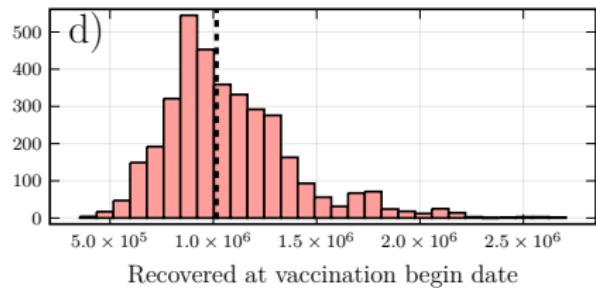
Youngest first



Uniform



Contact-based



**Figure:** Histogram of no. recovered at vaccination begin date, according to best strategy for that realization, over all parameter values in sensitivity analysis.  
Vertical lines are the median.

# Chapter Conclusion

- We described an age structured compartmental model of Sars-CoV-2 infection and vaccination coupled to a social model
- Showed that sometimes transmission interrupting strategies can be more effective
- Depends on the pre-existing immunity in the population

# Second Project

# Project 2

- Invasive forest pests cause incredible damage to ecosystems and lumber resources
- Evidence shows that movement of firewood is a major long distance vector
- Education and awareness is a major way we try to reduce this vector



**Figure:** an Emerald Ash Borer, which devastated Ash populations in North America

# Outline of project

- ① Adapt a model such as Barlow et al. (CITE) to a larger, more realistic network
- ② Use model to compare three possible prevention measures
  - Education/awareness
  - Inspection of moved firewood
  - Quarantine of highly susceptible forest patches
- ③ Assess measures across a range of parameter values and time horizons

# Model

$$\frac{dS_i}{dt} = \underbrace{rS_i \left(1 - \frac{(S_i + I_i)}{K}\right)}_{\text{Logistic Growth Of Forest}} - \underbrace{AS_i(I_i + B_i)\theta_k(I_i - I_a)}_{\text{Infestation term}} \quad (1)$$

$$\frac{dI_i}{dt} = \underbrace{-\gamma I_i}_{\text{Death of infested trees}} + \underbrace{AS_i(I_i + B_i)\theta_k(I_i - I_a)}_{\text{Susceptibles become infested}} - d \underbrace{\sum_{j=1, j \neq i}^N P_{j,i}(1 - C_e)(1 - L_j)I_j}_{\text{Total infested wood leaving due to transport}} \quad (2)$$

$$\frac{dB_i}{dt} = \underbrace{-\gamma B_i}_{\text{Decay of firewood}} + d \underbrace{\sum_{j=1, j \neq i}^N P_{i,j}(1 - C_e)(1 - L_j)I_j}_{\text{Import of fallen wood}} \quad (3)$$

$$\frac{dL_i}{dt} = \sigma L_i(1 - L_i) \left( \underbrace{U}_{\text{Net cost to transport firewood}} + \underbrace{s(2L_i - 1)}_{\text{Social influence term}} + \underbrace{fI_i}_{\text{Impact of infestation}} \right) \quad (4)$$

We use  $T_i(t)$ , computed from equation 5 to be the total number of infested trees in patch  $i$  up to time  $t$ .

$$\frac{dT_i}{dt} = AS_i(I_i + B_i)\theta_k(I_i - I_a) \quad (5)$$

Define  $T(t) = \frac{1}{N} \sum_{i=1}^N T_i(t)$  to be the average total number of infested trees up to  $t$ .

# Data

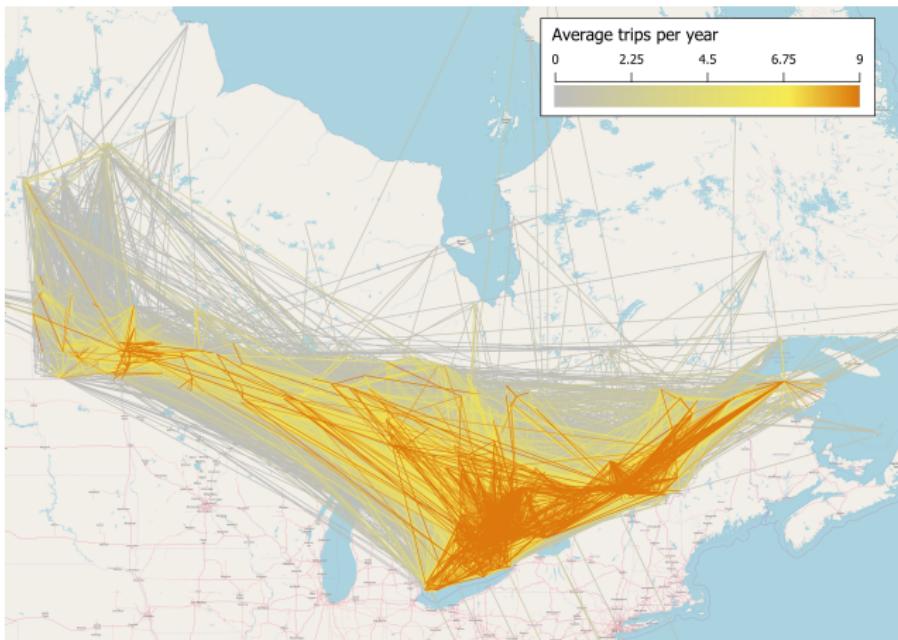
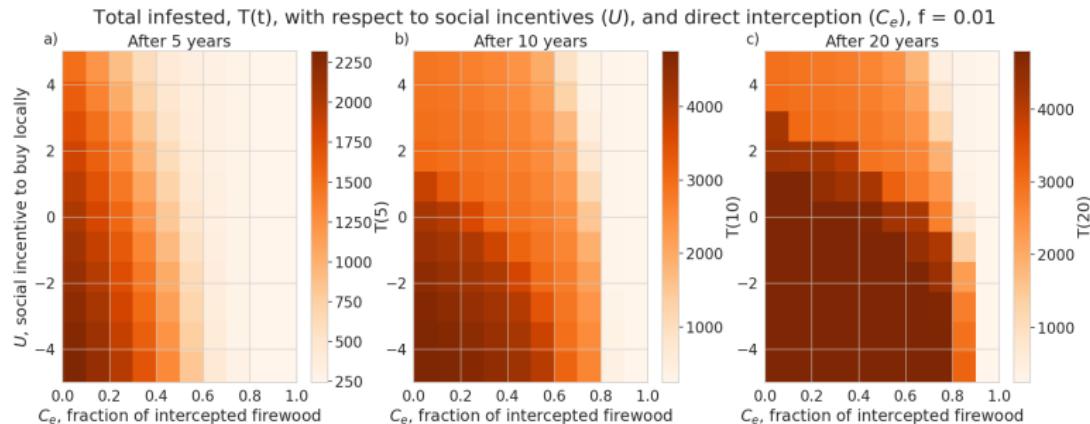


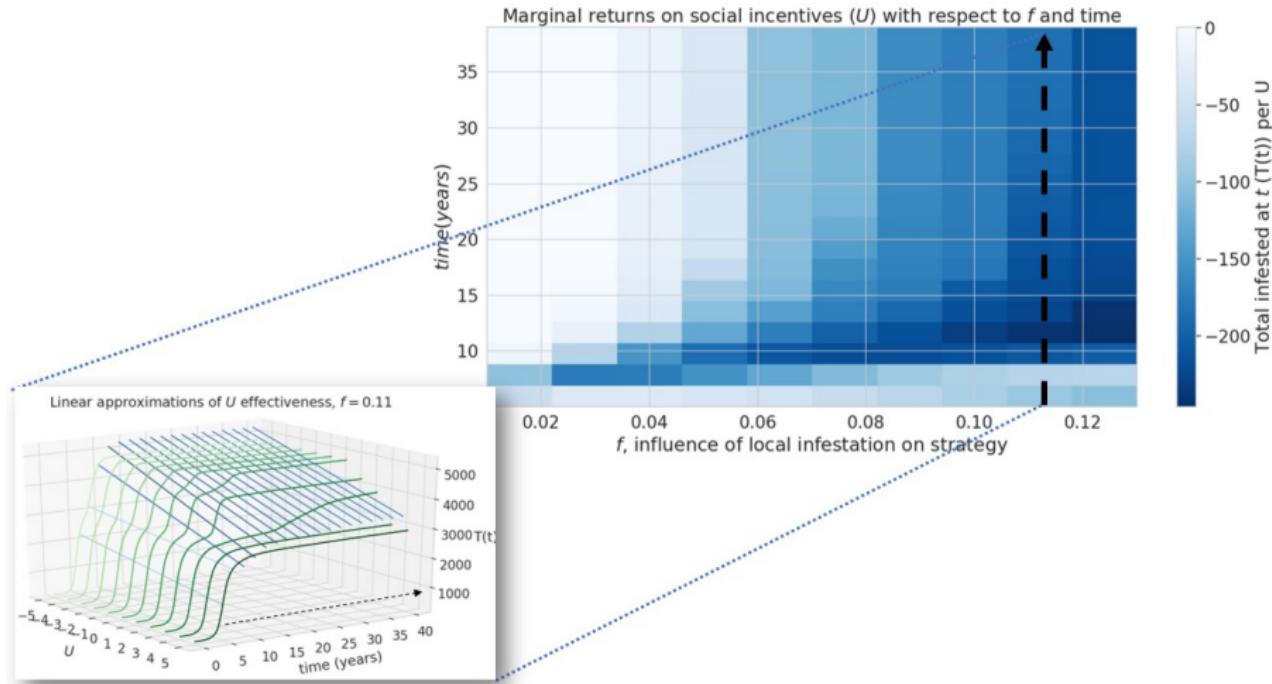
Figure: Travel network used to weight edges in firewood transport network

# Results



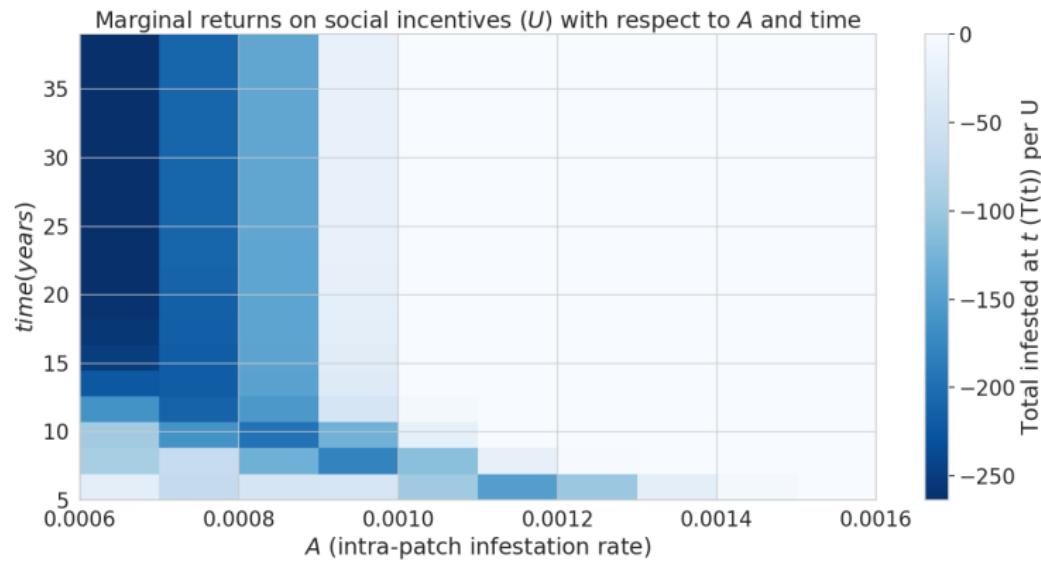
**Figure:** Total number of infested trees per node over 5 (a), 10 (b), and 20 (c) years

# Results



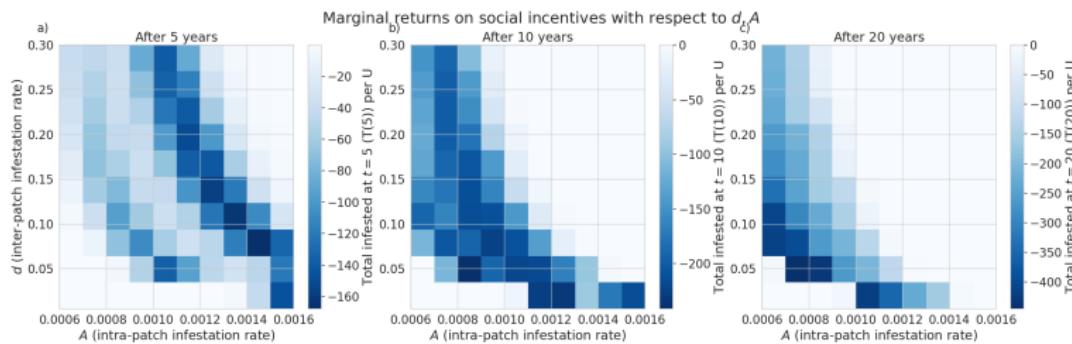
**Figure:** Efficacy of social incentives on infestation after time  $T$ . Inset graph shows an example of cross-section along the line  $f = 0.11$

# Results



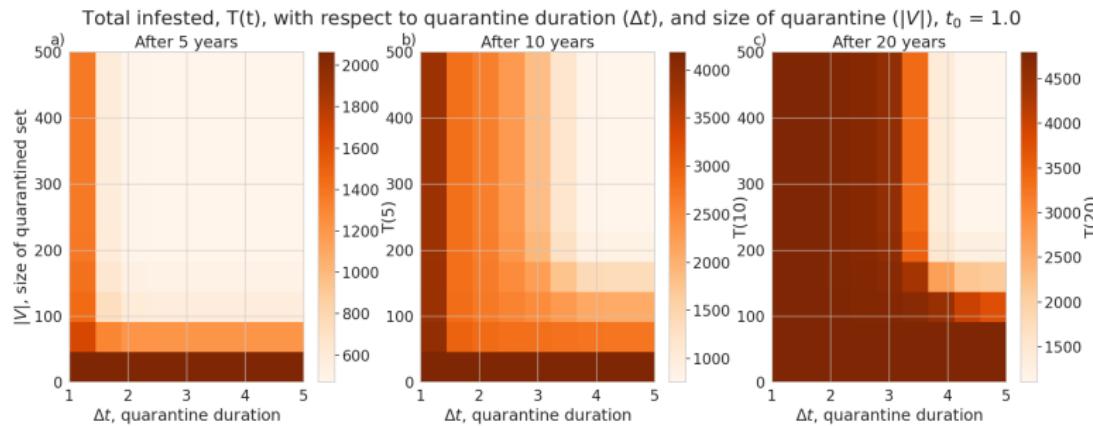
**Figure:** Efficacy of social incentives on infestation after time period  $T$  with respect to  $A$ , the intra-patch infestation parameter.

# Results



**Figure:** Efficacy of social incentives on infestation after time  $T$  intra-patch spreading rate  $A$ , affects infestation outcomes.

# Results



**Figure:** Average total infested trees ( $T(t)$ ) after 5, 10 and 15 years (panels a), b), and c) respectively), assuming the quarantine begins one year after the pest is introduced.

# Discussion

- Firewood inspection not likely to be effective in implementation
- Education, represented as social incentives, are able to decrease infection in the short term, but dependent on pest-specific parameters
- Patch quarantine can be effective if sufficiently many patches are isolated, and the pest is detected early

# Third Project

# Chapter 3

- Wildfire and bark beetles are disturbances integral to coniferous forest ecosystems in the western cordillera of North America
- Bark beetle outbreaks have always been destructive, but seem to be worse in recent decades
- Literature on causal relationship between bark beetle outbreaks and wildfire is extensive but inconclusive
- Existing modelling of these two coupled disturbances is sparse

# Research questions

How do changes in fire prevalence affect MPB dynamics?

How can we exploit stand structure to dampen MPB outbreaks?

Can we create a simple model that replicates major features of the Fire-MPB system?

# Project Outline

- Extend existing model of Duncan et al. to include wildfires
- Explore parameter regime of extended model
- Introduce forest stand thinning procedures to reduce MPB outbreaks
- Show that these stand thinning procedures are able to work due to increased stand heterogeneity

# Model

$$j_{n+1,1} = dJ_n + I_{n-2} + F_n \quad (6a)$$

$$j_{n+1,k} = (1-d)j_{n,k-1} - \frac{\alpha_1}{T} P_n j_{n,k-1}, \quad k = 2 \dots K-1, K \quad (6b)$$

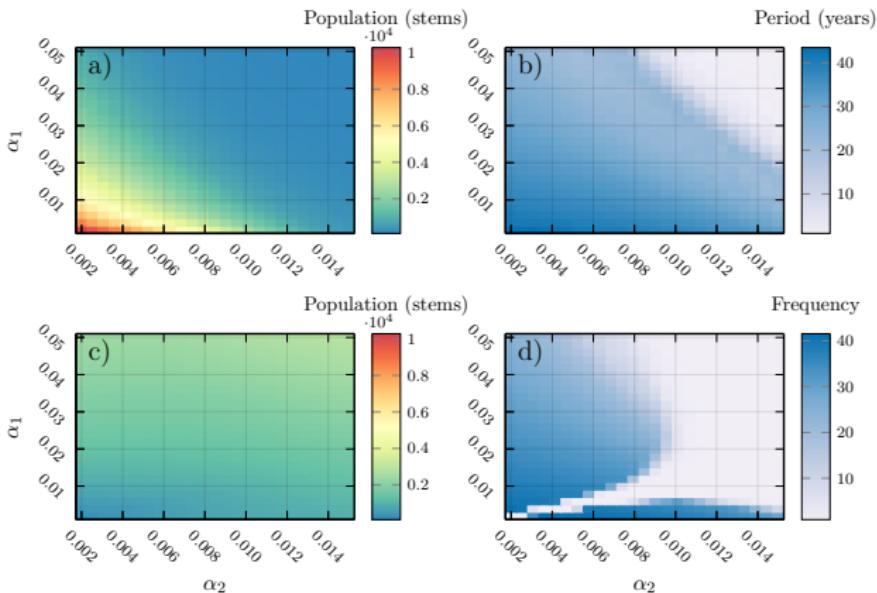
$$S_{n+1} = S_n + (1-d)j_{n,K} - \left( I_n + \frac{\alpha_2}{T} P_n I_n \right) - \frac{\alpha_2}{T} P_n (S_n + (1-d)j_{n,K}) - \sigma_F \gamma_n \quad (6c)$$

$$I_{n+1} = r_1 I_n e^{-\beta_1(T-S_{n+1})} - \frac{\alpha_2}{T} P_n I_n + \sigma_I \xi_n \quad (6d)$$

$$F_{n+1} = P_n \left[ \frac{\alpha_1}{T} \sum_{k=1}^{K-1} j_{n,k} + \frac{\alpha_2}{T} (S_n + (1-d)j_{n,K}) + \frac{\alpha_2}{T} I_n \right] + \sigma_F \gamma_n \quad (6e)$$

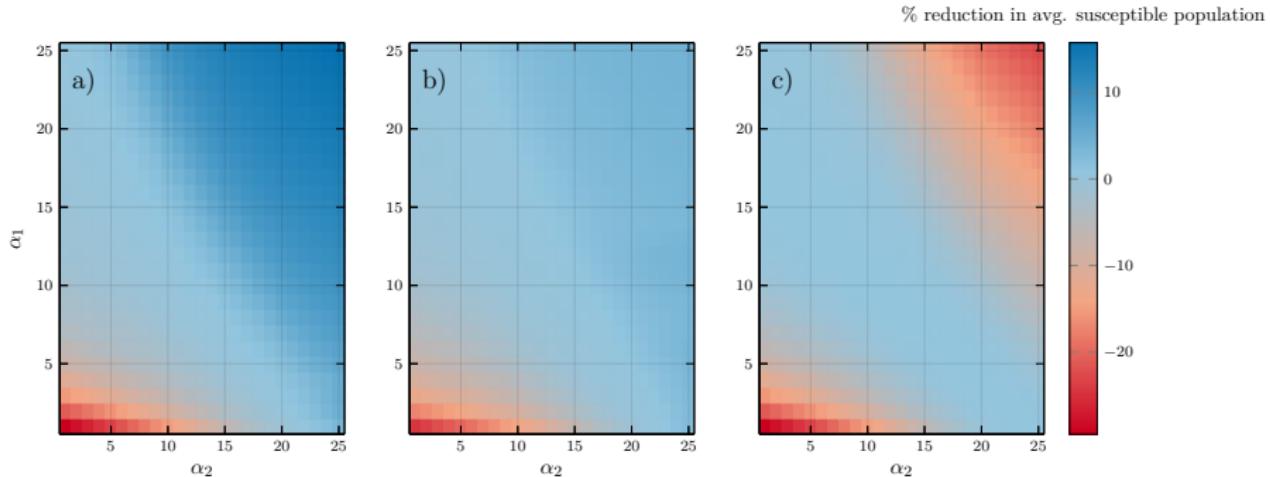
$$P_n = T - \sum_{i=1}^n F_i e^{-\kappa(n-i)} \quad (6f)$$

# Results



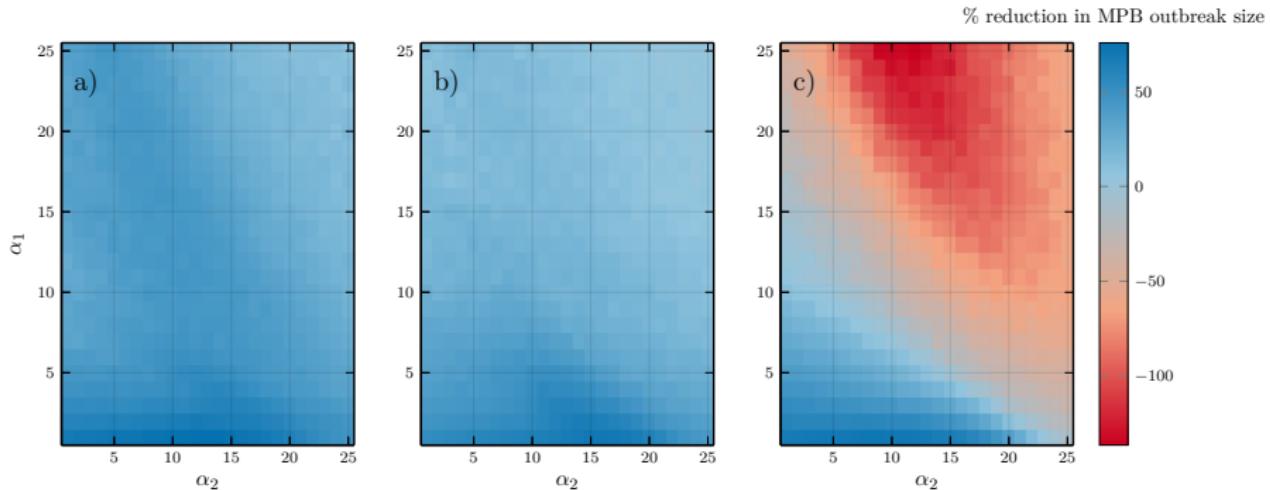
**Figure:** Panels: a) Average size of largest MPB population, b) Average frequency of MPB outbreaks, c) Average size of largest fire season, d) Average frequency of severe fire seasons. All measured at equilibrium.

# Results



**Figure:** Percentage change in average susceptible (mature) forest population compared to no FTP with a)  $\tau = 0.15, m = 8$ , b) with  $\tau = 0.15, m = 8$  applied every 5 years, c) controlled burning with  $\tau = 0.15, m = 8$ , with respect to burning rates  $\alpha_1, \alpha_2$ .

# Results



**Figure:** Percentage change in maximum MPB infestation size within 500 year period under FTP with a)  $\tau = 0.15, m = 8$ , b) with  $\tau = 0.15, m = 8$  applied every 5 years, c) controlled burning with  $\tau = 0.15, m = 8$ , with respect to burning rates  $\alpha_1, \alpha_2$ .

# Chapter Conclusion

- We show that increasing fire prevalence is able to dampen MPB outbreaks by increasing stand heterogeneity
- Stand heterogeneity can also be increased through forest thinning or prescribed burning, which also dampens MPB outbreaks.
- These results are consistent with ecological evidence Seidl et al. (2016) and Kaufmann et al. (2008)

-  Bubar, Kate M et al. (2020). "Model-informed COVID-19 vaccine prioritization strategies by age and serostatus". In: *medRxiv*.
-  Buckner, Jack H, Gerardo H Chowell, and Michael R Springborn (2020). "Optimal Dynamic Prioritization of Scarce COVID-19 Vaccines". In: *medRxiv*.
-  Kaufmann, Merrill R et al. (2008). "The status of our scientific understanding of lodgepole pine and mountain pine beetles: a focus on forest ecology and fire behavior". In.
-  Seidl, Rupert et al. (2016). "Spatial variability in tree regeneration after wildfire delays and dampens future bark beetle outbreaks". In: *Proceedings of the National Academy of Sciences*, p. 201615263.