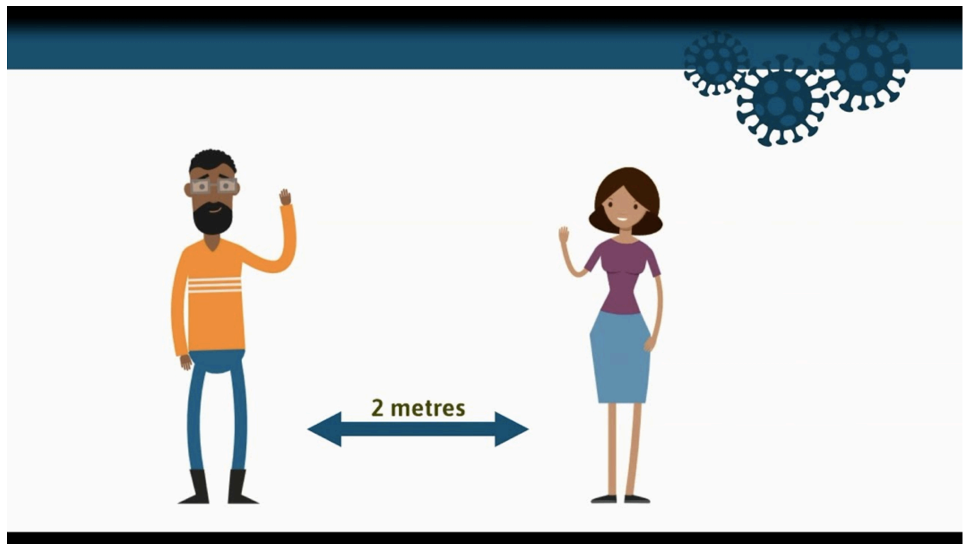
Assessing potential COVID-19 outcomes for a university campus with and without physical distancing



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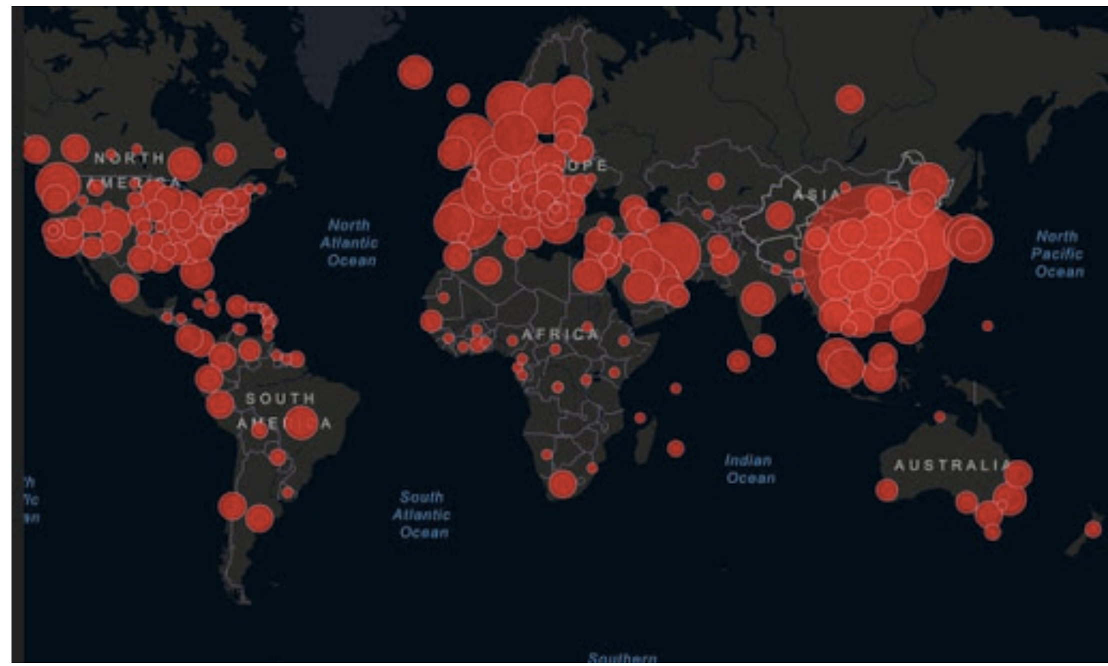
Outline

- Background
- Urgent study requested
- March 12, 2020 “snapshot in time”
- Mathematical model



- Potential scenarios based on known data
- Decisions made
- Further developments since.

Background

- COVID-19 is a respiratory disease with flu-like symptoms
- The causative agent of a potentially fatal disease that has significant public-health concerns
- It originated and gained traction in Wuhan, China, in late 2019.

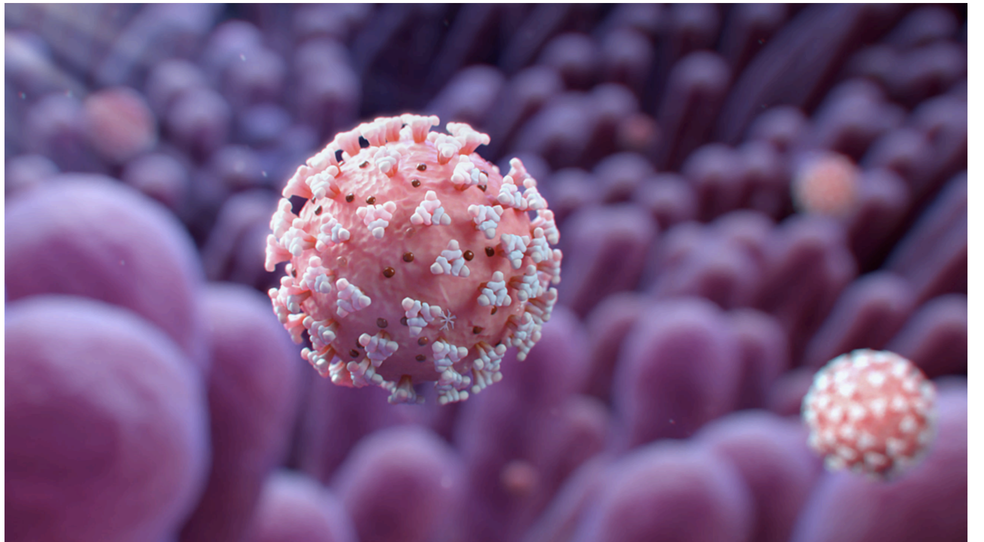
Symptoms

- Common symptoms:
  - fever
  - cough
  - fatigue;

- Other symptoms:
  - sputum production
  - headache
  - haemoptysis
  - diarrhoea
  - dyspnoea
  - lymphopenia.

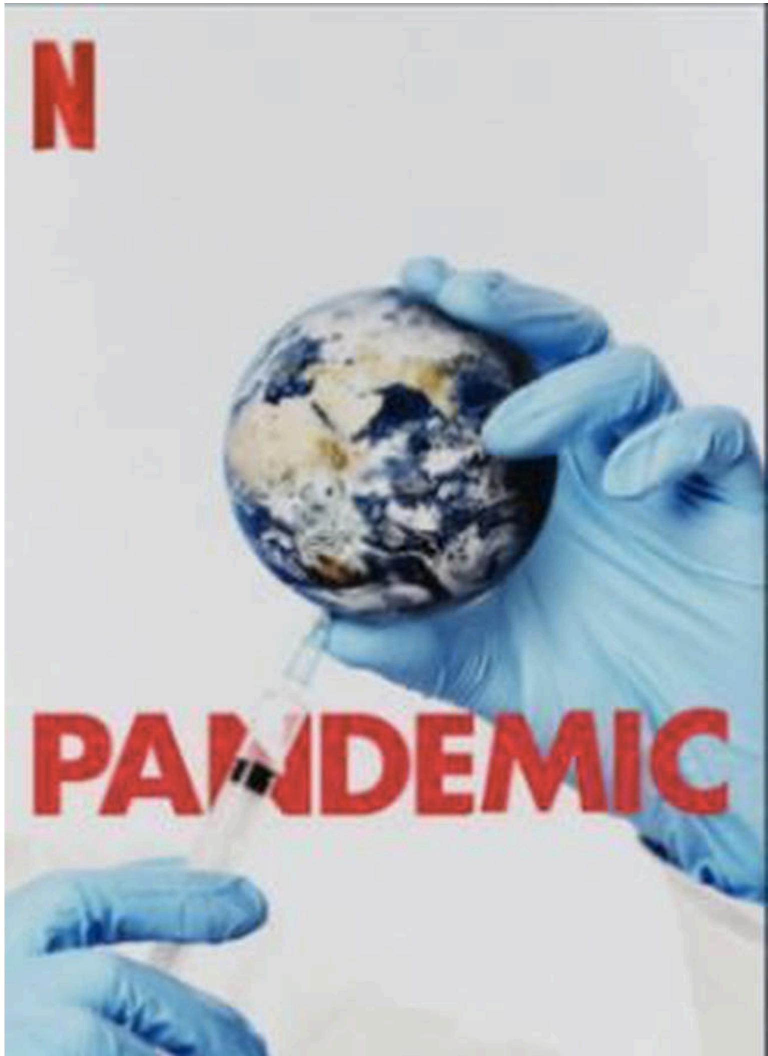
Death

- Period of onset of symptoms to death ranges from 6–41 days
- Median of 14 days
- Depends on age and immune status
  - for people under 70, the median is 20 days (range 10–41).



Timeline

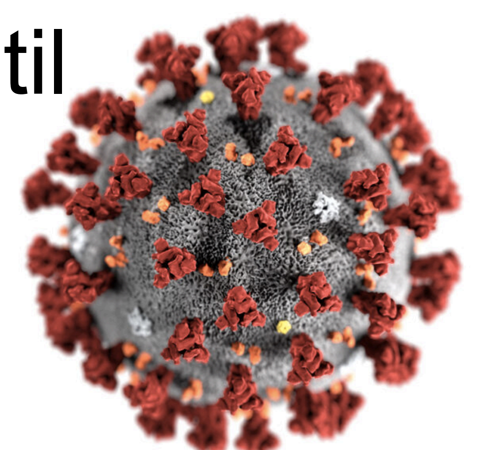
- Jan 22: 425 laboratory-confirmed cases in Wuhan
  - initially estimated R_0=2.2
  - doubling time of 7.4 days
- Feb 16: 51,857 cases
- Mar 3: 90,870 cases
- Mar 11: >118,000 cases
  - declared a pandemic by the World Health Organization.



The problem

On March 12, the University of Ottawa (Canada) requested an informal modelling study to answer the following questions:

1. What combinations of transmission rates and serial intervals make for the best case?
   – and which for the worst?
2. What is the consequence for outbreak size and potential mortality for waiting until Case #1 physically appears on campus, versus being proactive?



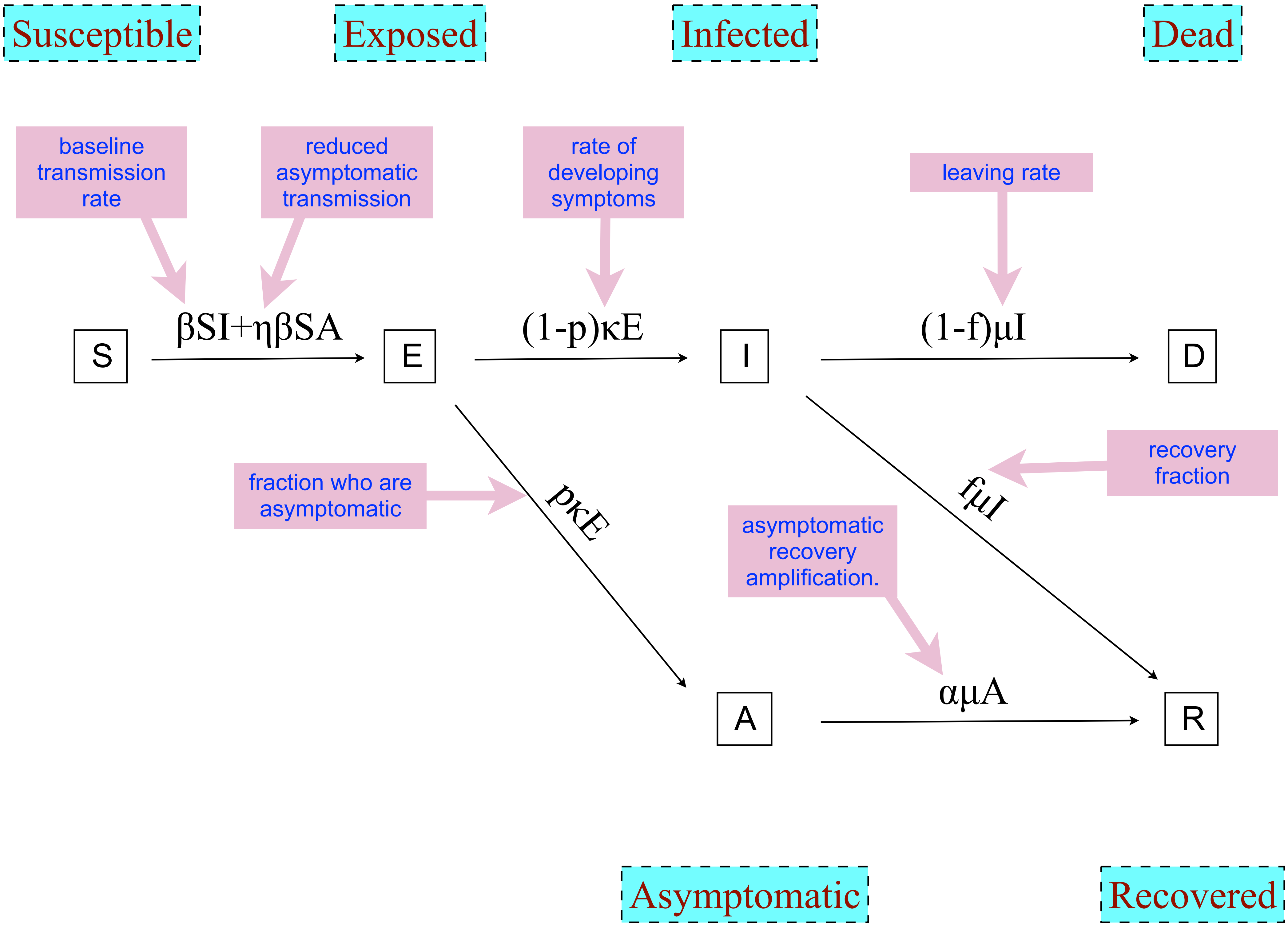
SEIARD

Our model consists of six compartments:

- Susceptible individuals (S)
- Exposed individuals (E)
- Symptomatic individuals (I)
- Asymptomatic individuals (A)
- Recovered individuals (R)
- Dead individuals (D).

Definitions

- We define symptomatic individuals as those who have symptoms and are capable of transmitting the virus
- Asymptomatic individuals can also transmit, but likely at a lower rate
  - these individuals may recover faster
- Exposed individuals are infected but not yet infectious
- Death is only due to disease
- No replacement of susceptibles.

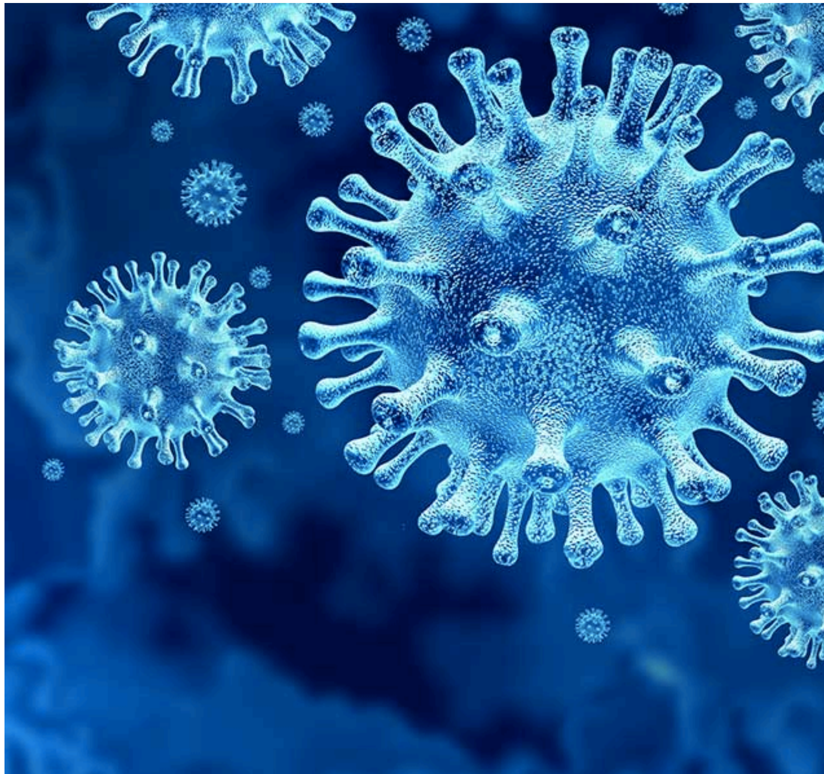


Susceptible
Exposed
Infected
Dead
baseline transmission rate
reduced asymptomatic transmission
rate of developing symptoms
leaving rate
βSI+ηβSA
(1-p)κE
(1-f)μI
S
E
I
D
recovery fraction
fμI
fraction who are asymptomatic
pκE
asymptomatic recovery amplification.
αμA
A
R
Asymptomatic
Recovered

The model

- The differential equation model is given by

$$
\begin{aligned}
S' &= -\beta SI - \eta\beta SA \\
E' &= \beta SI + \eta\beta SA - \kappa E \\
I' &= (1-p)\kappa E - \mu I \\
A' &= p\kappa E - \alpha\mu A \\
R' &= f\mu I + \alpha\mu A \\
D' &= (1-f)\mu I.
\end{aligned}
$$



S=susceptibles E=exposed I=infected A=asymptomatic R=recovered D=dead β=transmission η=asymptomatic transmission reduction κ=infection rate p=asymptomatic proportion μ=recovery/death rate α=asymptomatic recovery amplification f=recovery proportion

Data

On March 12, we knew the following:

- 17% of the population was asymptomatic
- The low-risk death rate was 0.2%
  - most individuals on campus are low risk
- The incubation rate was 3 days (range 0–24)
- It takes 20 days from onset of symptoms to death (range 10–41)
- The reproduction number R_0 was 2.35 (range 1.15–4.77)
- The campus population was 42,000 people.

Caveats

- In the early stages of a fast-moving epidemic, data is often scarce or unreliable
- These numbers were the most accurate that were available at the time
- Not all individuals would be on campus at any given moment
  - so N is likely an overestimate
- There is significant heterogeneity in the susceptible population.

DFE

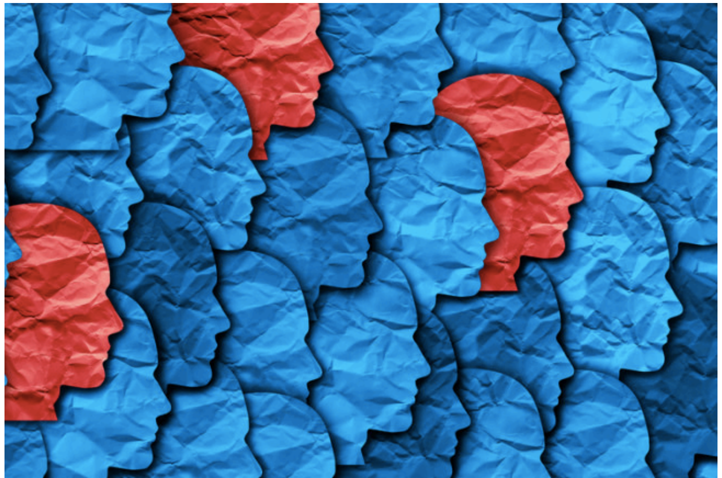
- The disease-free equilibrium is given by

$$(S, E, I, A, R, D) = (N, 0, 0, 0, 0, 0),$$

where N is the total campus population

- Initial conditions are

$$S(0) = N \qquad E(0) = 0 \qquad I(0) = 1$$
$$A(0) = 0 \qquad R(0) = 0 \qquad D(0) = 0.$$



S=susceptibles E=exposed
I=infected A=asymptomatic
R=recovered D=dead
N=campus population

Reproduction number

- Using the next-generation method, we have

$$F = \begin{bmatrix} 0 & \beta N & \eta\beta N \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad V = \begin{bmatrix} \kappa & 0 & 0 \\ -(1-p)\kappa & \mu & 0 \\ -p\kappa & 0 & \alpha\mu \end{bmatrix}$$

$$FV^{-1} = \begin{bmatrix} \frac{\beta N(1-p)}{\mu} + \frac{\eta\beta N p}{\alpha\mu} & \frac{\beta N}{\mu} & \frac{\eta\beta S}{\alpha\mu} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

- The reproduction number is thus

$$R_0 = \frac{\beta N(1-p)}{\mu} + \frac{\eta\beta N p}{\alpha\mu}$$

N=campus population β=transmission
η=asymptomatic transmission reduction κ=infection rate
p=asymptomatic proportion
μ=recovery/death rate
α=asymptomatic recovery amplification f=recovery proportion

Contributions from symptomatic individuals

Contributions from asymptomatic individuals.

Determining transmission

- Since we know R_0, we can use that to determine likely β values
- Substituting known data and rearranging, we have

$$\beta = \frac{2.35\alpha}{697200\alpha + 142800\eta}.$$

R_0=reproduction number β=transmission
η=asymptomatic transmission reduction
α=asymptomatic recovery amplification

Possible scenarios

1. Asymptomatic individuals are identical to symptomatic individuals ($\eta=\alpha$)
   - in this case, $\beta=2.7976\text{x}10^{-6}$
2. Asymptomatic individuals do not infect susceptibles ($\eta=0$)
   - in this case, $\beta=3.3706\text{x}10^{-6}$
3. Asymptomatic individuals are 50% as transmissible as symptomatic individuals but recover twice as fast ($\eta=0.5$, $\alpha=2$)
   - in this case, $\beta=3.20644\text{x}10^{-6}$.

β=transmission η=asymptomatic transmission reduction
α=asymptomatic recovery amplification

Long-term outcomes

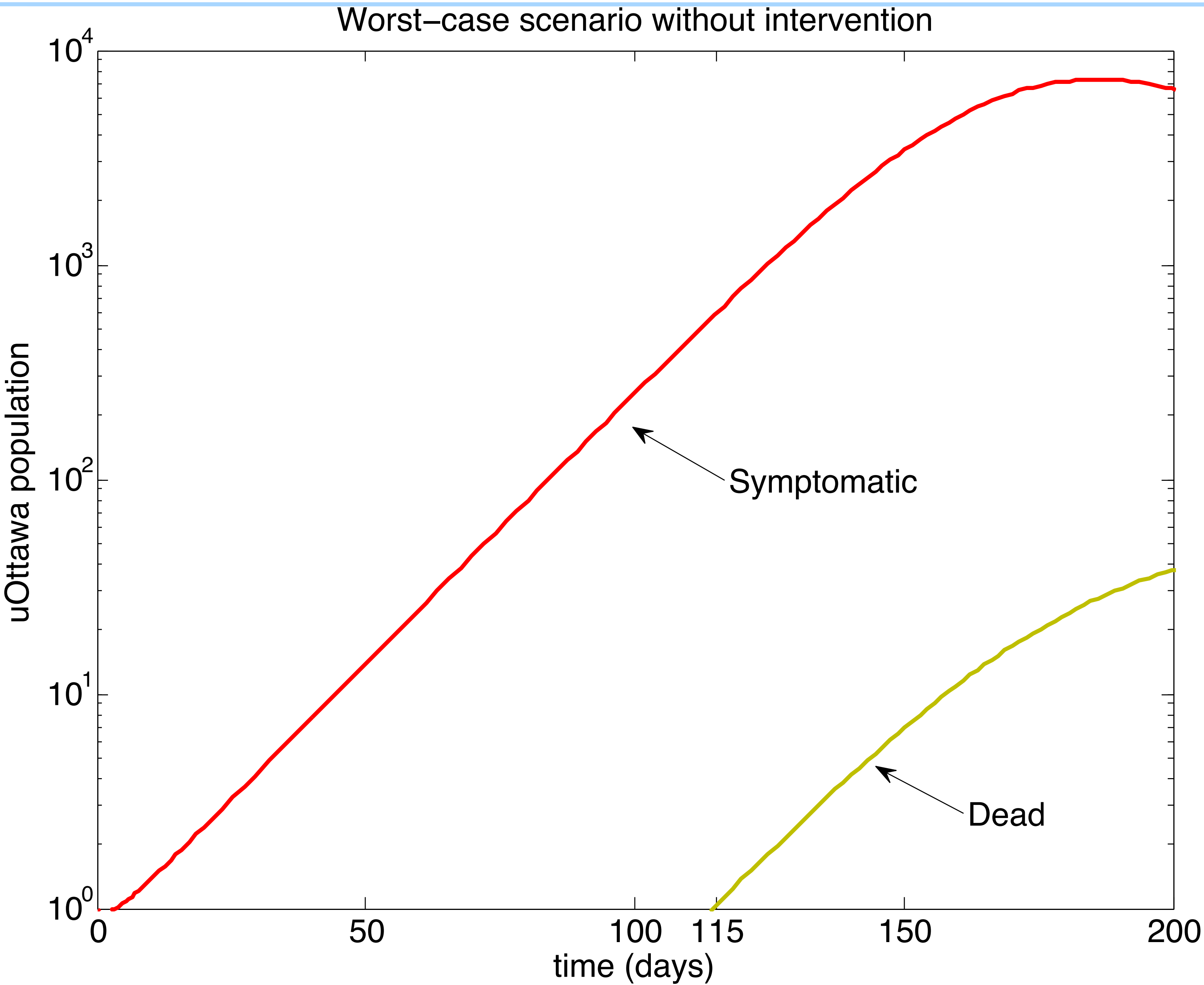
- Using different values of β, we ran several simulations to determine possible long-term outcomes

  (i) in the absence of interventions and

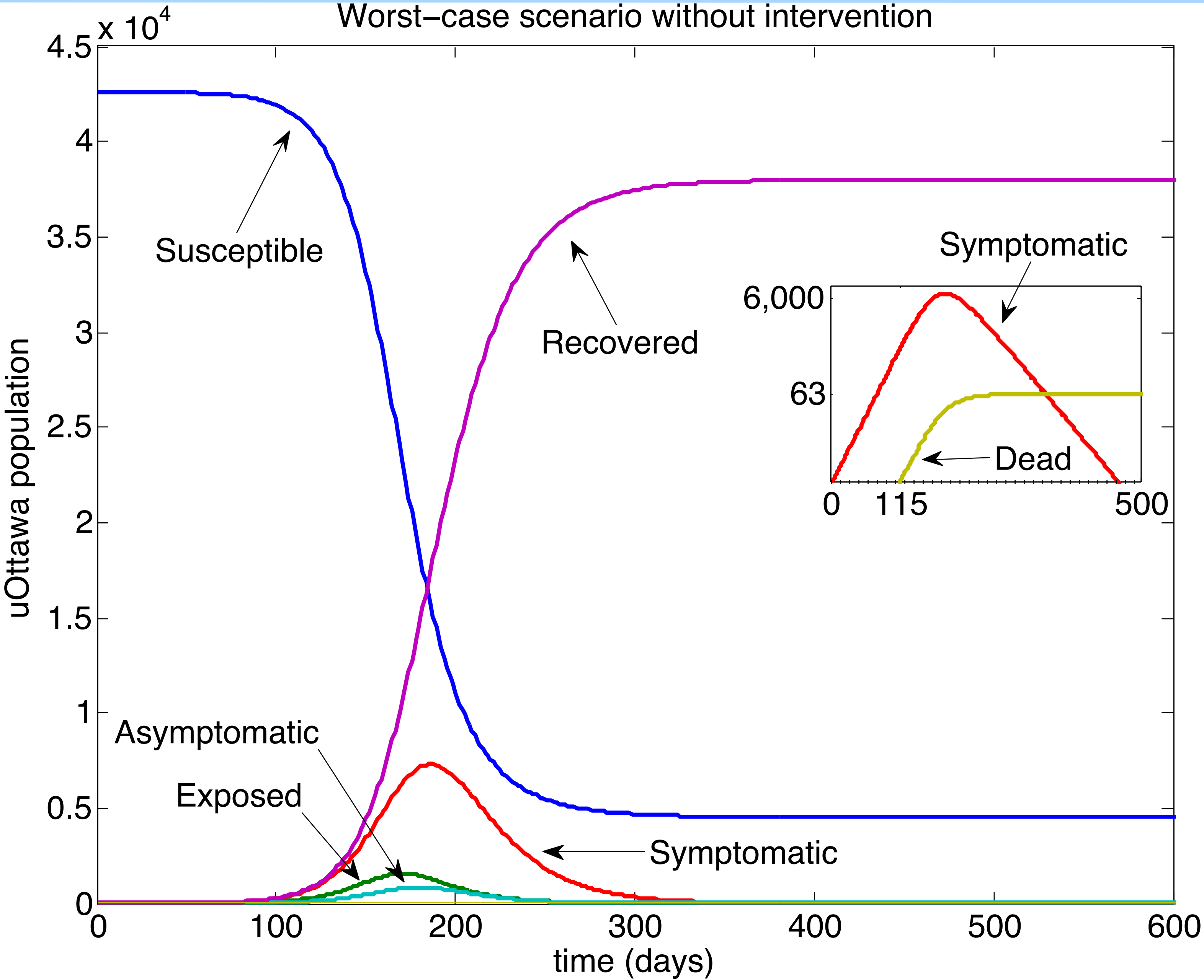
  (ii) if contact rates are cut by 50%.

β=transmission

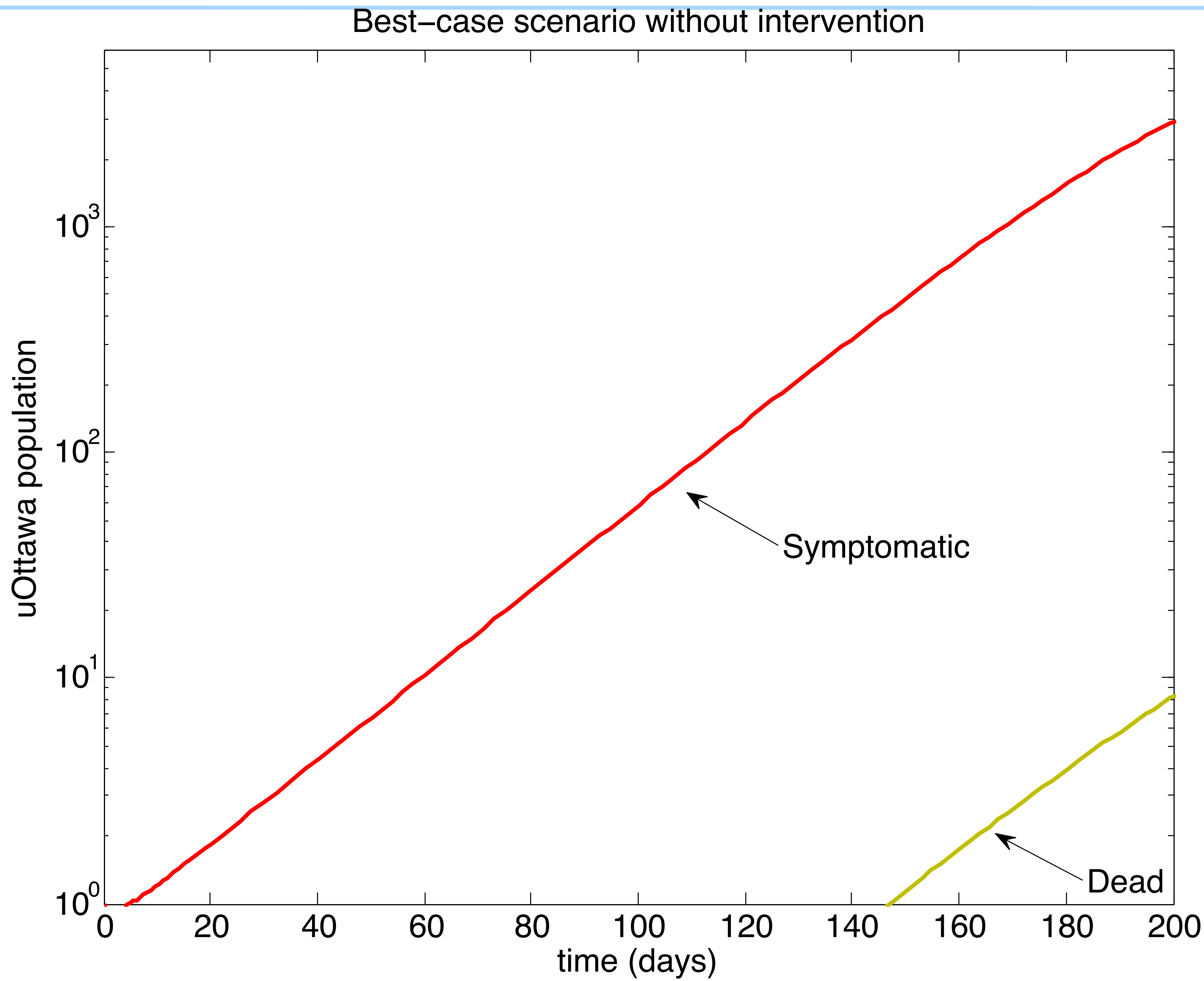
High transmission, no intervention



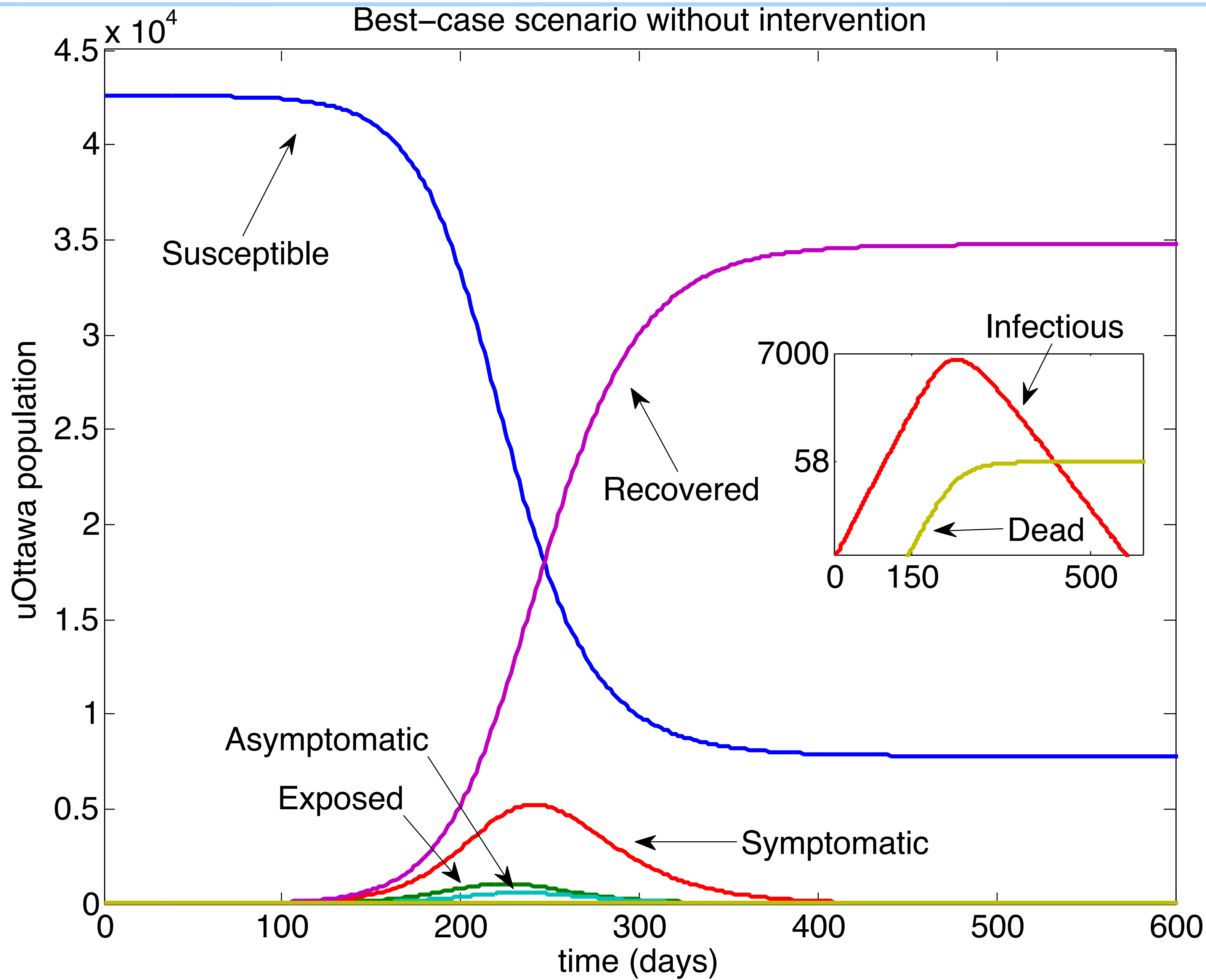
High transmission, no intervention



Low transmission, no intervention

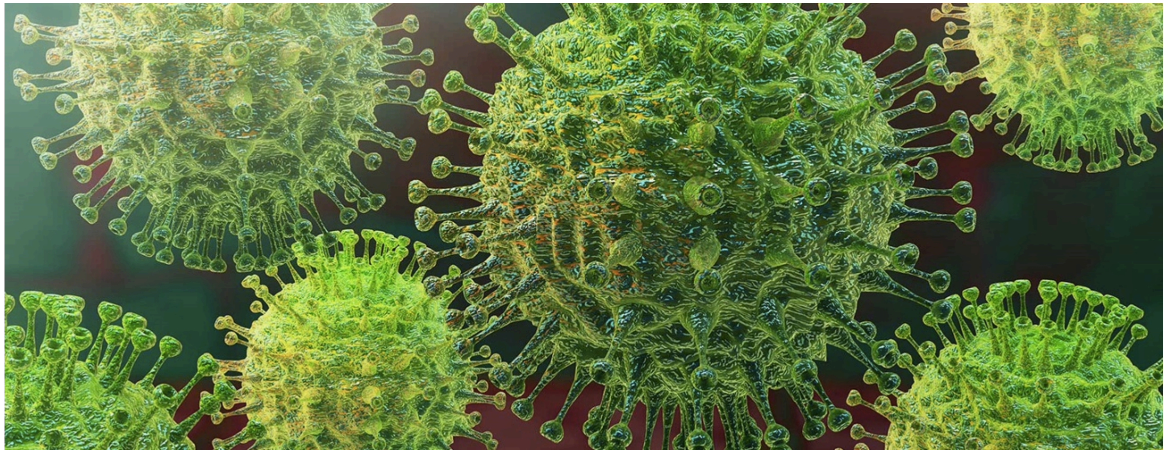


Low transmission, no intervention

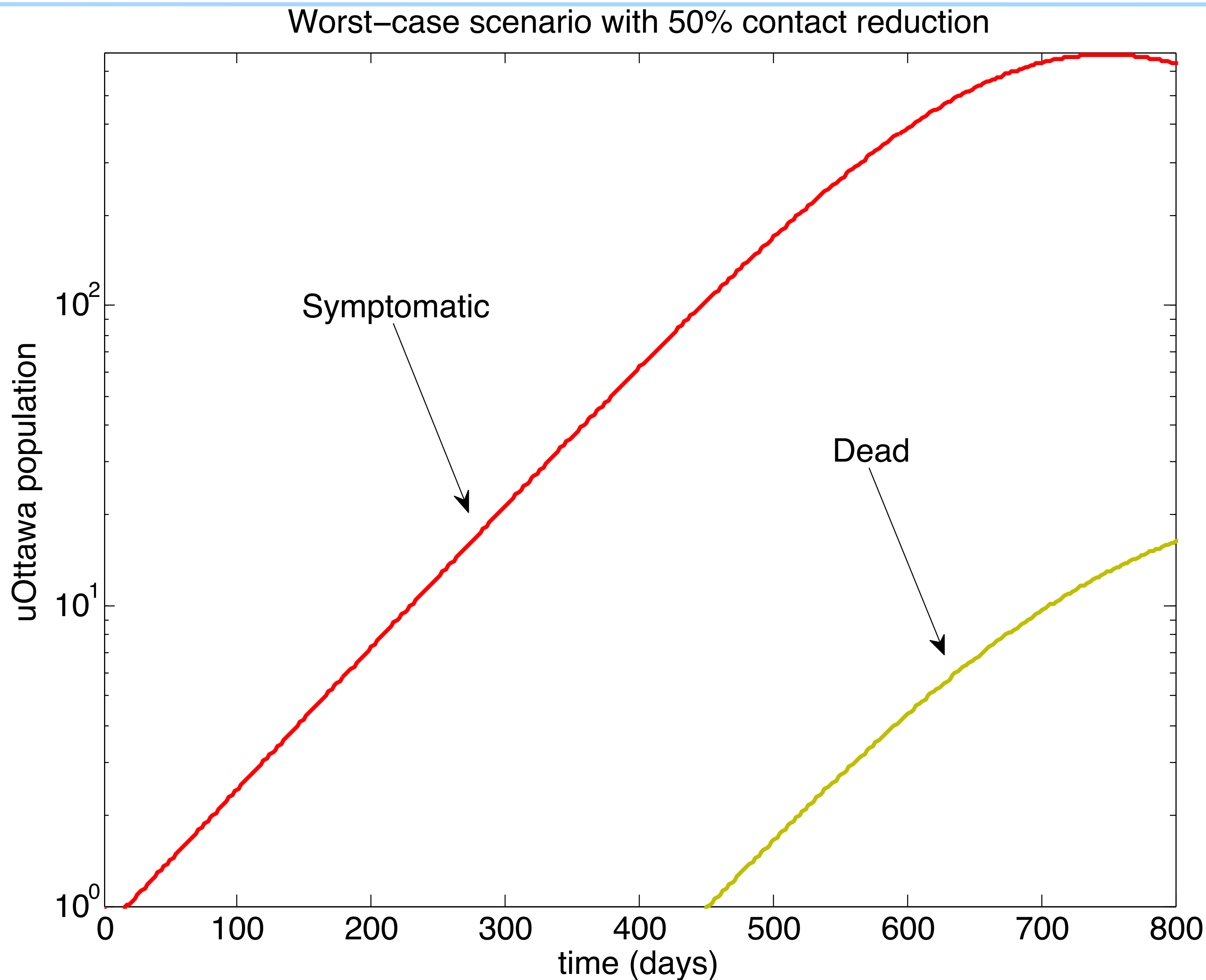


Without intervention

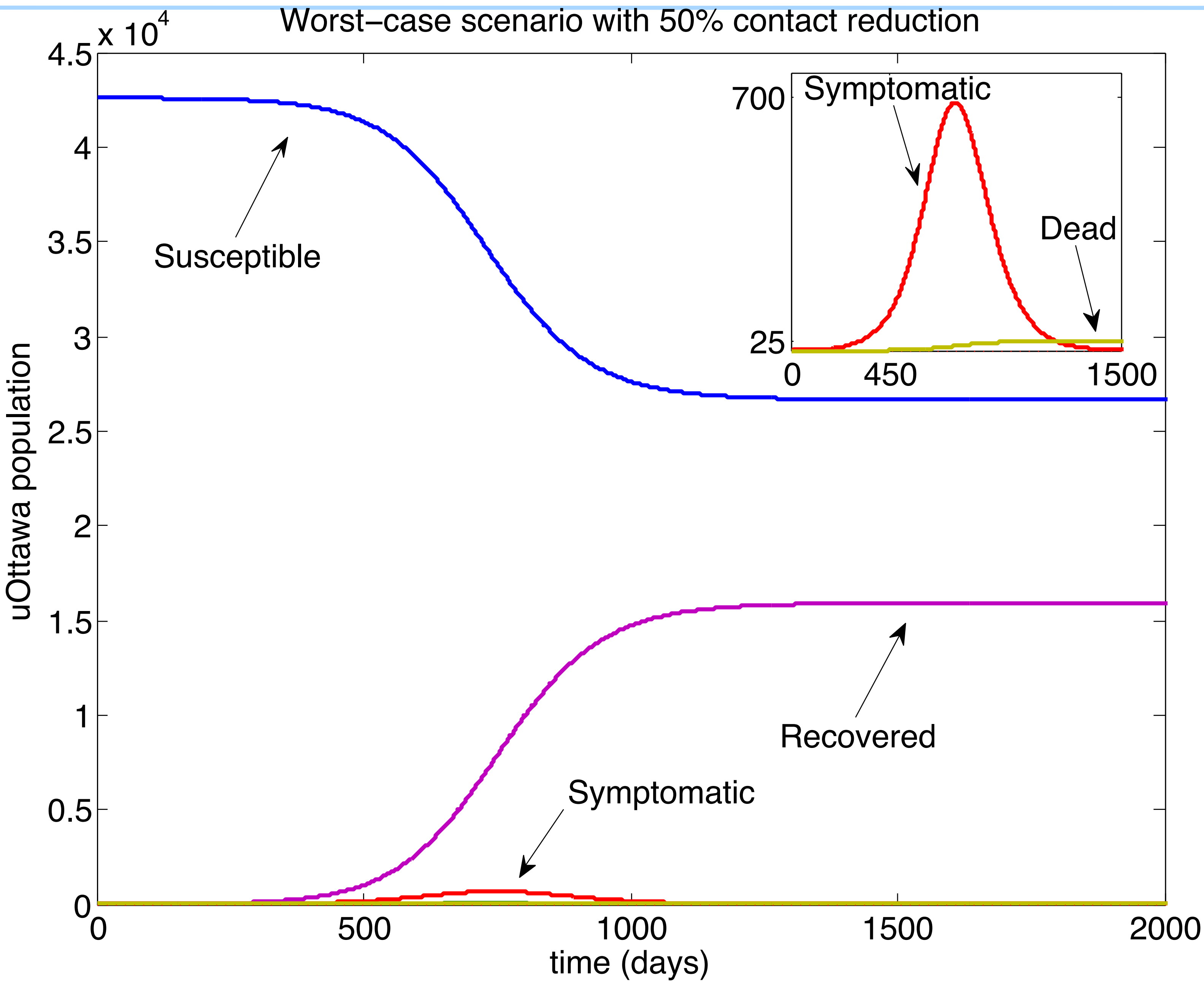
- The worst-case scenario results in the first death 115 days after the first symptomatic individual is diagnosed
  – eventually leading to 63 deaths
- The best-case scenario has the first death occurring 150 days after the first diagnosis
  – eventually leading to 58 deaths.



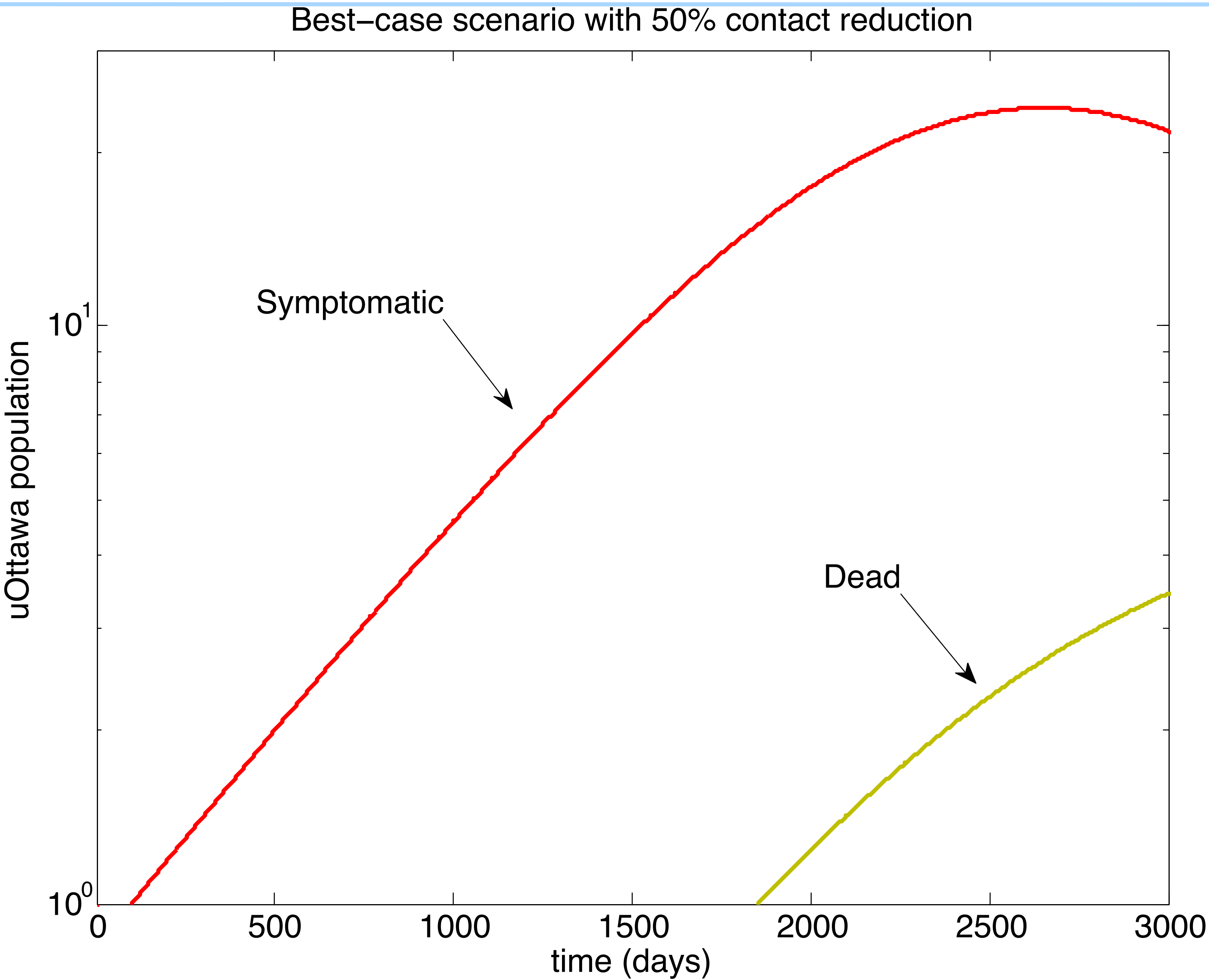
High transmission, half the contacts



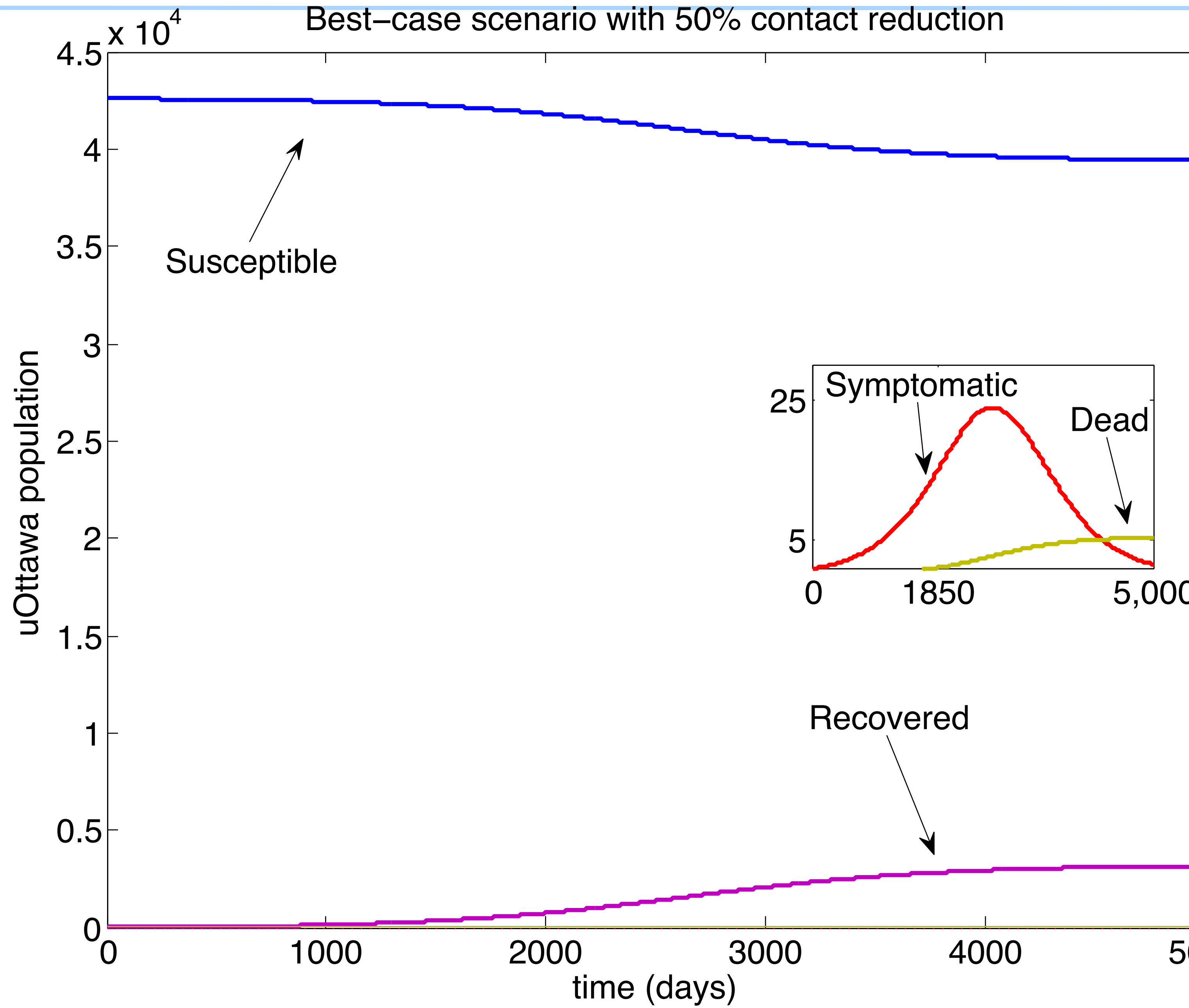
High transmission, half the contacts



Low transmission, half the contacts



Low transmission, half the contacts



Reducing contacts by half

- For high transmission, the first death occurs 450 days after the first diagnosis (vs. 115)
  - eventually leading to 25 deaths (vs. 63)
- For low transmission, the first death occurs 1850 days after the first diagnosis (vs. 150)
  - eventually leading to 5 deaths (vs. 58)
- It follows that the reduction of contacts is critical.

Outcome

- On March 13, one day after receiving these results...

  ...the university closed campus entirely
- It remained closed, except for essential research
  - e.g., labs that cannot be left unattended
- The Summer 2020, Fall 2020 and Winter 2021 semesters were all online.

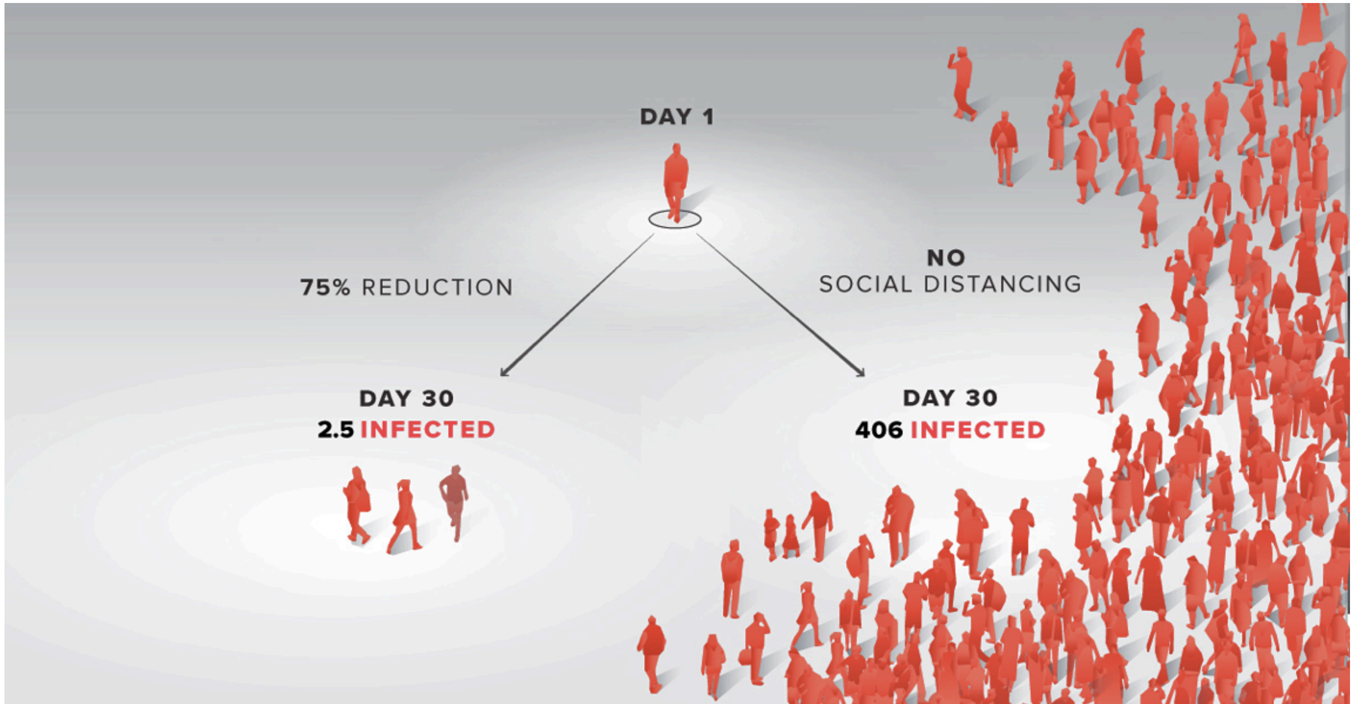
Roads not taken

- Since March 12, significant information about COVID-19 has come to light
- The global lockdown changed the course of these predictions
- There were no deaths on campus...

  ...but a case on July 17, 2020, in a member of the support staff was discovered on July 20.

The Ottawa pandemic

- The outbreak in Ottawa followed the typical age distribution for COVID-19
- There were significant infections in
  - hospitals
  - retirement homes
  - long-term care facilities
- But few in the community.



Current Status of Ottawa COVID-19 Confirmed Cases, as of 2pm on 2020-08-15

Confirmed COVID-19 Cases

2701

Deaths

264

Crude Case Fatality 9.8%

Change from Previous Report

Cases : +3 +0.1%

Deaths : 0 0.0%

Hospitalized

Currently 12

Cumulative 269

Intensive Care Unit

Currently 1

Cumulative 66

Active Cases

112 4.1%

Resolved Cases

2325 86.1%

Health Care Worker/ First Responder

621 23.0%

Figure 1. Cumulative number of Ottawa residents with confirmed COVID-19, by the EARLIEST of onset, test and reported date; and deaths from COVID-19 by date of death

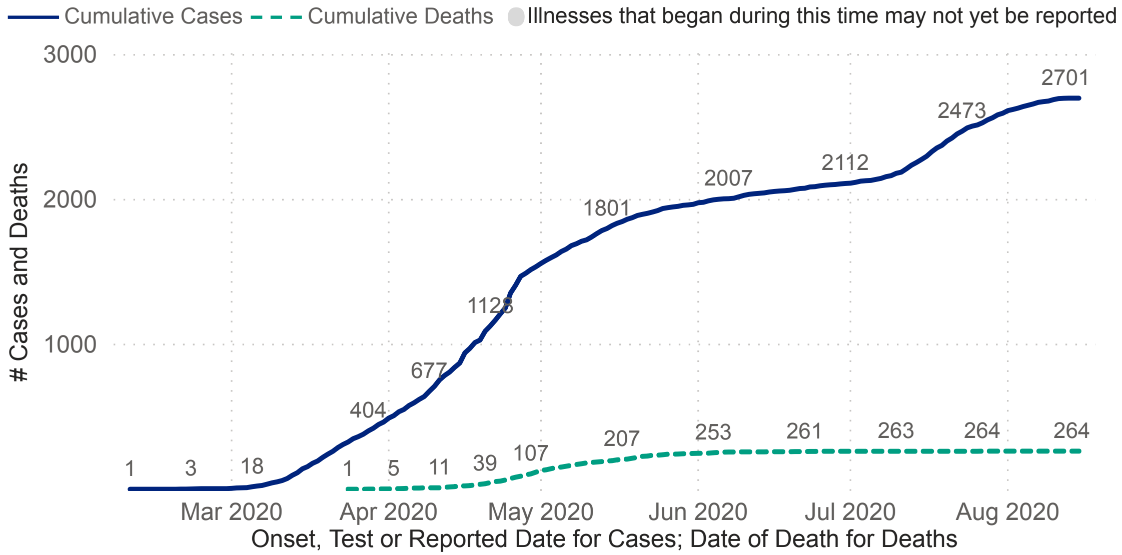
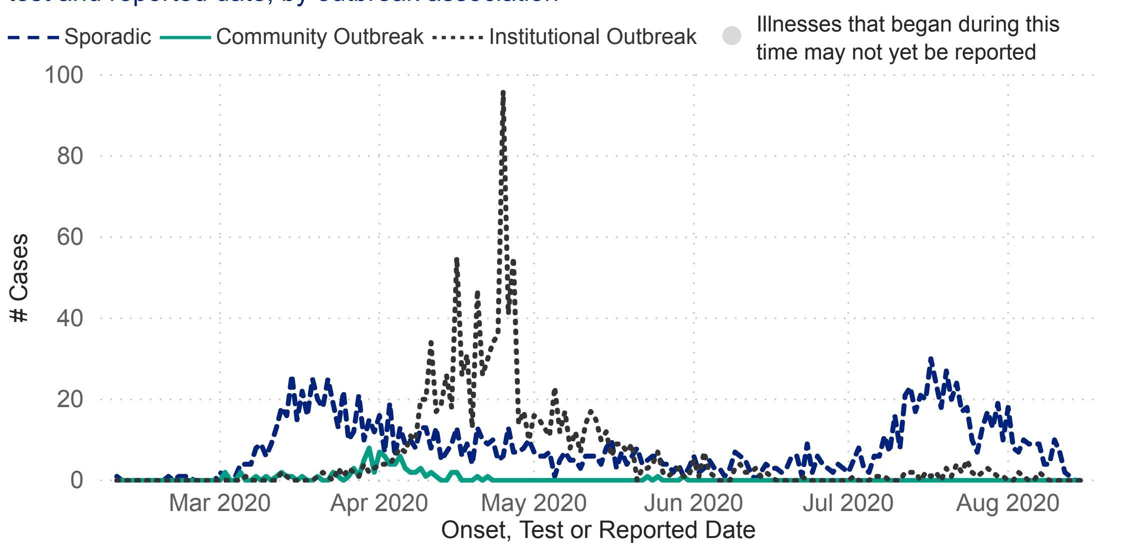


Figure 2. Number of Ottawa residents with confirmed COVID-19, by the EARLIEST of onset, test and reported date, by outbreak association



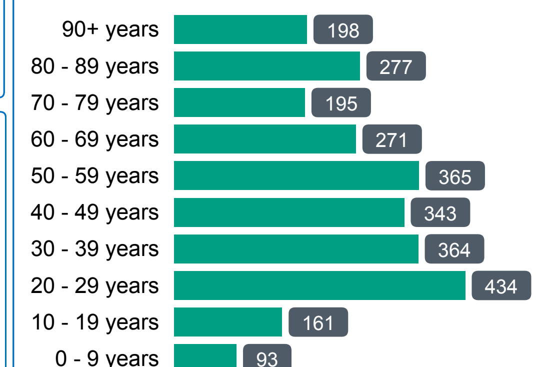
Outbreaks

3 Ongoing Outbreaks in Healthcare & Childcare Establishments

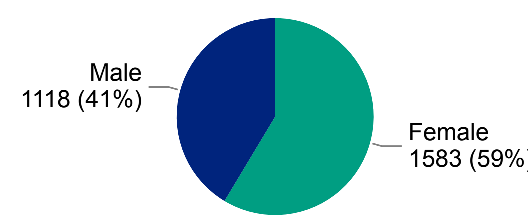
New Outbreaks : 0

Type of Establishment	COVID-19 Outbreak Related Deaths
RH	11
LTCH	223
Hospital	4
Total	**238**

Age



Gender

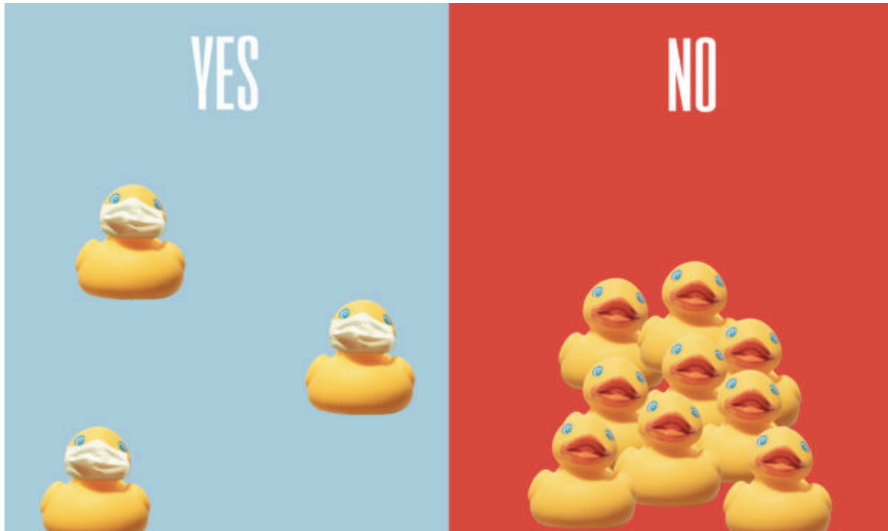


The first wave

- Ottawa’s first wave ended in July
- ~2000 cases and ~260 deaths
  - population of 1.4 million
- Sporadic cases peaked in mid-to-late March at 27 cases/day
- A much larger outbreak in long-term care facilities peaked at 93 cases/day on April 25.

Modelling campus reopening

- What if we reopened campus, with appropriate caution?
  - this of course happened, but much later
- eg masks, partial remote learning
- Contacts with symptomatic people would be significantly lower
- This would offset their higher rate of viral shedding compared to asymptomatic individuals.



Younger individuals

- For a campus population of primarily younger individuals, we had matched the death rate to that of younger individuals
- Campus might consist primarily of asymptomatic individuals
  - since younger people are less affected by the disease.

Proportional symptomatic rate

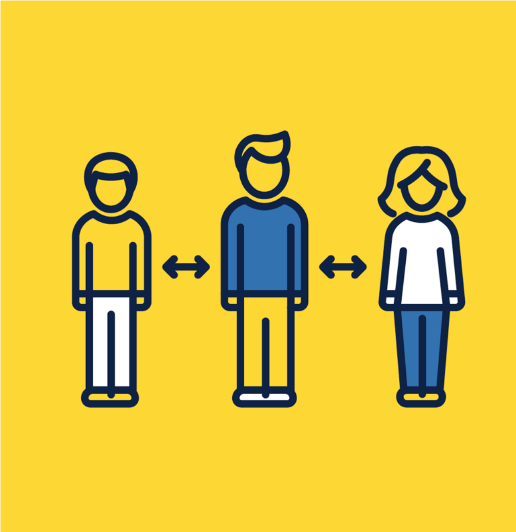
- If the death rate is proportional to the symptomatic rate, this suggests the following ratio:

$$\frac{\text{population death rate}}{\text{population symptomatic rate}} = \frac{\text{campus death rate}}{\text{campus symptomatic rate}}$$

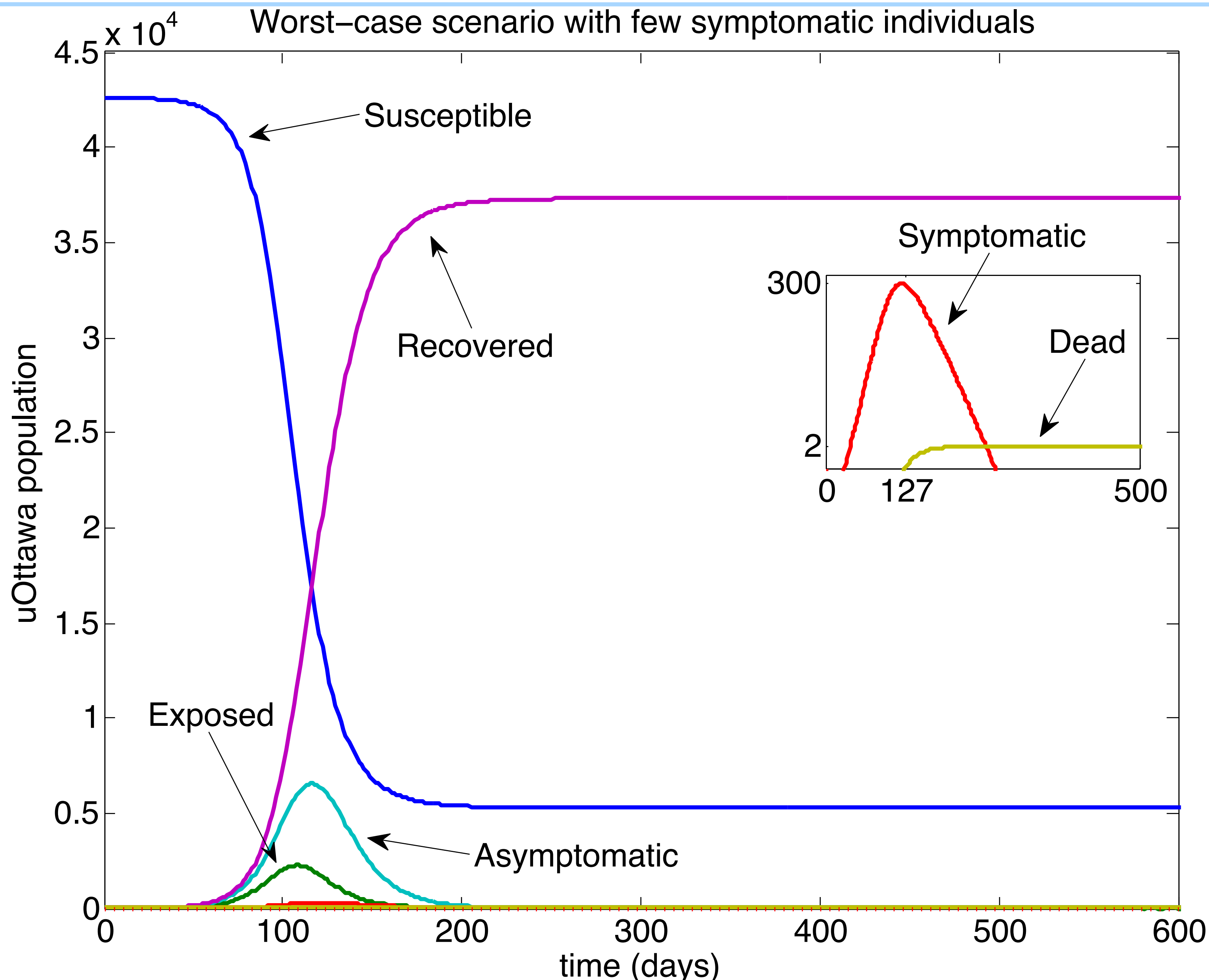
$$\frac{0.0628}{1-0.17} = \frac{0.002}{\text{campus symptomatic rate}}$$

- From this, we have p=0.9736 and $\beta = 10.369\text{x}10^{-6}$
  - in the case where α=2 and η=0.5.

β=transmission η=asymptomatic transmission reduction p=asymptomatic proportion α=asymptomatic recovery amplification

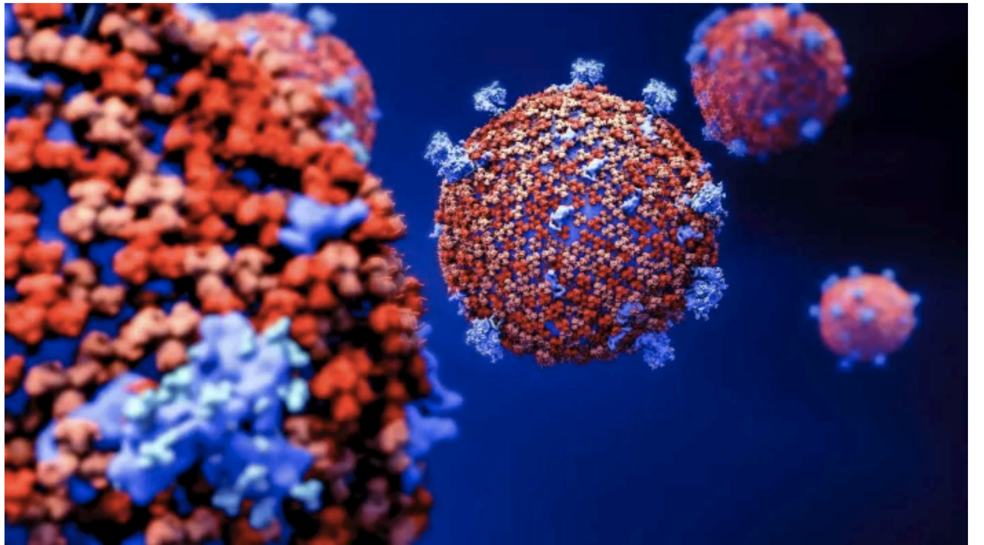


A potential future?



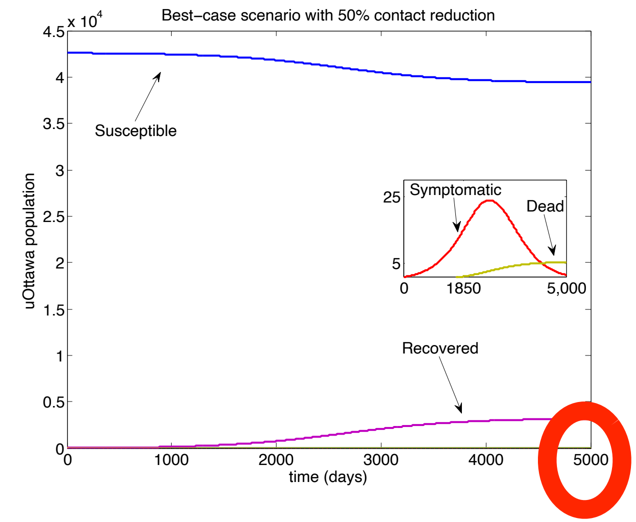
Reduced peak and deaths

- In this case, the number of symptomatic individuals peaks at 300 instead of 6000
- The first death is predicted at a similar time
  - 127 days after first diagnosis, instead of 115
- The total number of deaths is kept at 2
  - other cases produce similar results.



Lockdown

- We are not suggesting that lockdown remain in place for 13 years (5000 days)
  - it is up to political leaders to decide if 2, 25 or 63 deaths on a university campus is acceptable
- The lockdown contact reduction was almost certainly more than 50% among students
- However, this is likely heterogeneous
  - e.g., if students are essential workers.



Limitations

- This was a “snapshot in time”
- The available data was limited
- The model does not consider vital dynamics
  - no influx of new susceptibles
  - constant population
- The former is likely true
- However, university policies may change as a result of lockdown
  - e.g., fewer international students
  - an increase in distance learning via zoom.

Model limitations

- We assumed mass-action transmission
  - this assumes individuals are well-mixed
- This assumption may not hold in lockdown
  - the number of contacts is reduced
  - so is the strength of their interactions
- Recovered individuals were assumed to be immune to reinfection
  - we now know that this is not true.

Benefits

- The benefits of this model were:
  - its rapid development
  - its flexibility in considering multiple cases where data was lacking
  - its ability to directly answer questions posed by the university administration

- We have thus seen the role that models can play during a fast-moving pandemic
- Shown their power to make predictions
- Illustrated their ability to inform policy when linked to decision-making processes.

Conclusion

- These results illustrate the interface between theoretical mathematics, numerical simulations, real-world data and human behaviour
- By modelling the disease during the early stages of a pandemic, a variety of potential scenarios could be assessed quickly, using the information available at the time
- Decisions could then be made by the administration, armed with useful predictions.

Key reference

- R.J. Smith?, Assessing potential COVID-19 outcomes for a university campus with and without physical distancing (Proceedings of the SummerSim-SCSC 2020 conference, 2020, Article 34, pp1–10)

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