Georgia Tech Health & Humanitarian Systems
Interdisciplinary Research Center

Modeling Infectious Diseases: Projecting Spread, Evaluating Interventions, and Resource Allocation

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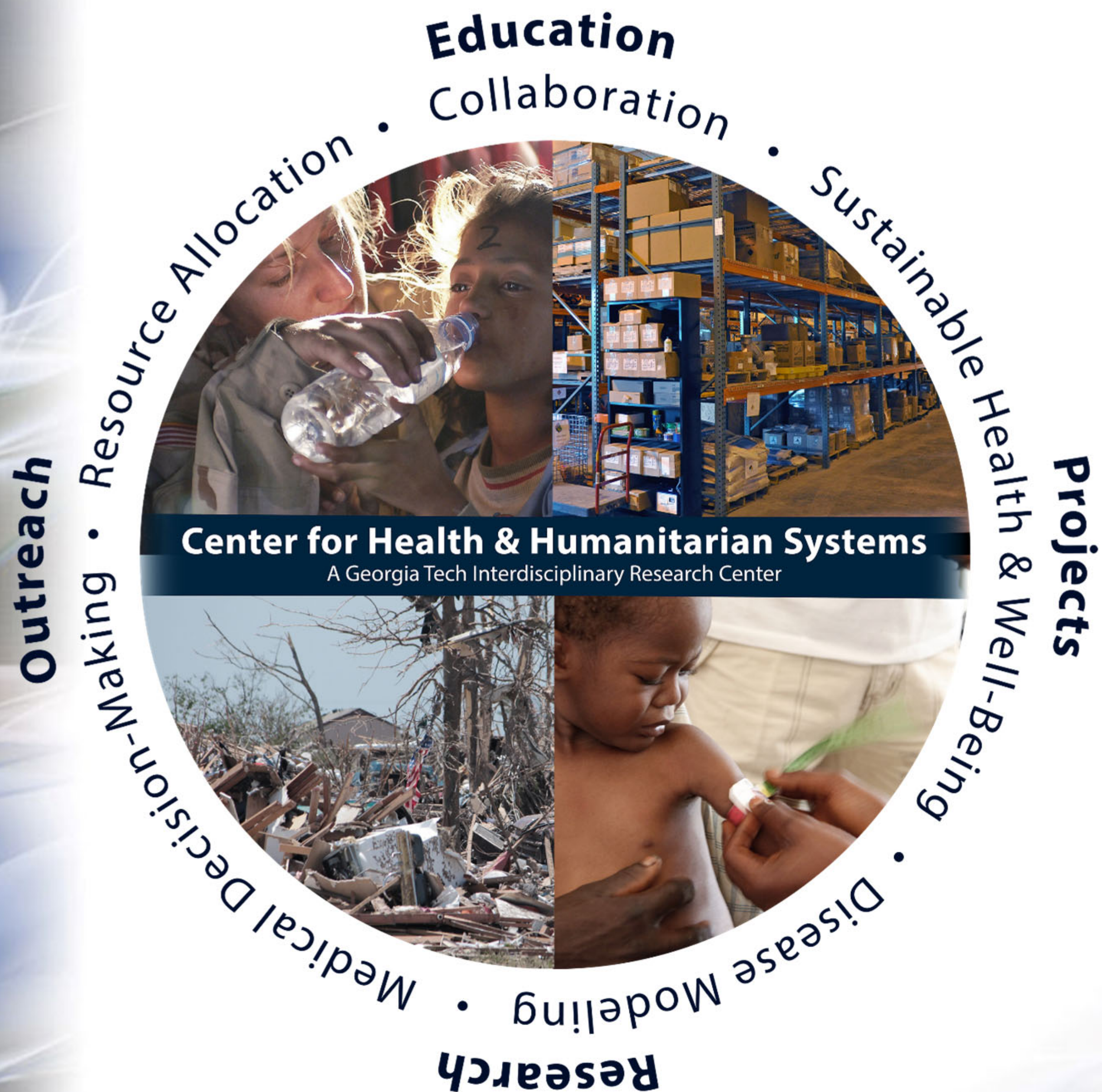

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Make a positive "impact" through improved health & humanitarian systems worldwide

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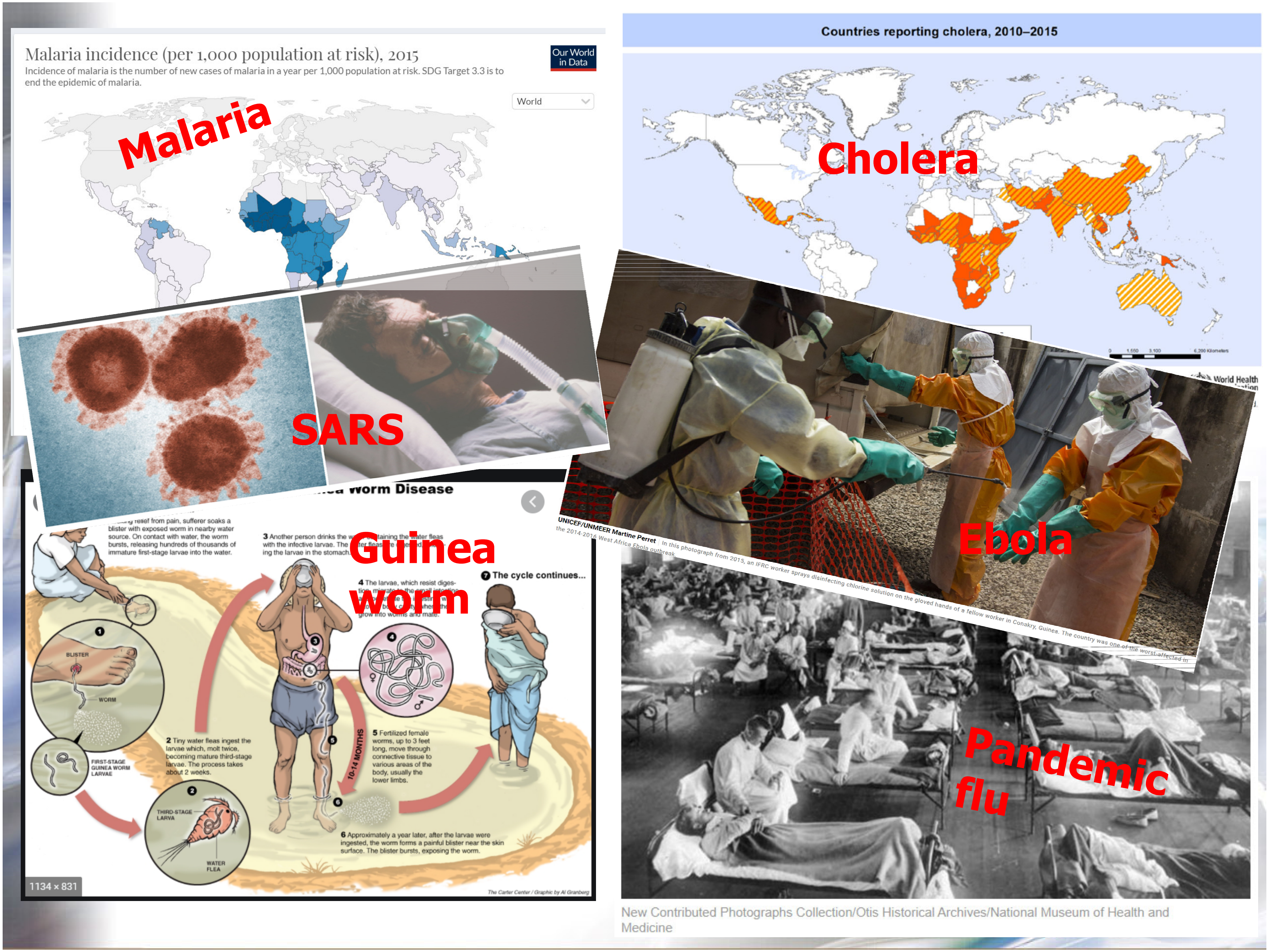
Malaria incidence (per 1,000 population at risk), 2015
Incidence of malaria is the number of new cases of malaria in a year per 1,000 population at risk. SDG Target 3.3 is to end the epidemic of malaria.
Our World in Data
World
Malaria
Countries reporting cholera, 2010–2015
Cholera
SARS
Ebola
UNICEF/UNMEER Martine Perret
Worm Disease
blister with exposed worm in nearby water source. On contact with water, the worm bursts, releasing hundreds of thousands of immature first-stage larvae into the water.
3 Another person drinks the
with the infective larvae.
ing the larvae in the stomach.
Guinea worm
The cycle continues...
BLISTER
WORM
FIRST-STAGE GUINEA WORM LARVAE
2 Tiny water fleas ingest the larvae which, molt twice, becoming mature third-stage larvae. The process takes about 2 weeks.
THIRD-STAGE LARVA
WATER FLEA
10-14 MONTHS
5 Fertilized female worms, up to 3 feet long, move through connective tissue to various areas of the body, usually the lower limbs.
6 Approximately a year later, after the larvae were ingested, the worm forms a painful blister near the skin surface. The blister bursts, exposing the worm.
1134 × 831
The Carter Center / Graphic by Al Granberg
Pandemic flu
New Contributed Photographs Collection/Otis Historical Archives/National Museum of Health and Medicine

Source: *Nigeria Health Online, 2016*

Prevention

Insecticide nets
Indoor residual spraying
Vaccines

Source: *Medicins Sans Frontieres, 2015*

Surveillance

Monitoring of confirmed malaria cases

Source: *Making Malaria History, 2014*

Treatment

Rapid diagnostic tests and artemisinin-based combination therapy

Source: *Nigeria Health Online, 2016*

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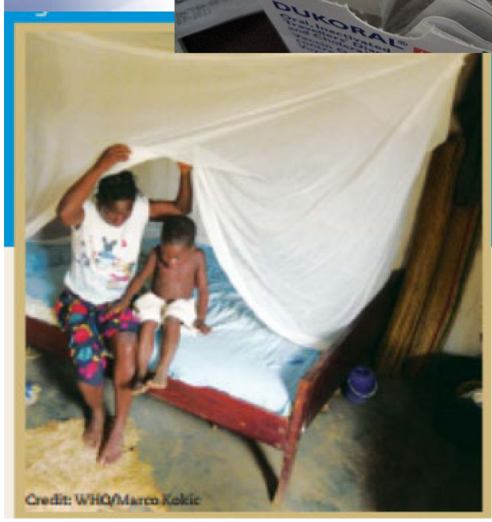
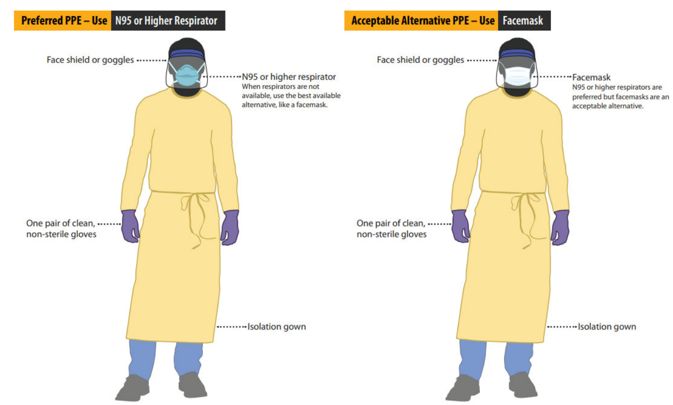


Credit: WHO/Marco Kokic



www.cdc.gov/coronavirus

Source: Carter Center

With the assistance of his colleagues, Wegwa Odol Othow (yellow shirt) measures a pond for application of a safe larvicide that helps stop the Guinea worm life cycle.

Disease Models → Decision-Making

- Understanding and projecting the disease spread
- Evaluating the impact of intervention strategies
- Estimating resource needs
- Resource planning and allocation

Geographically and over time,

by sub-populations

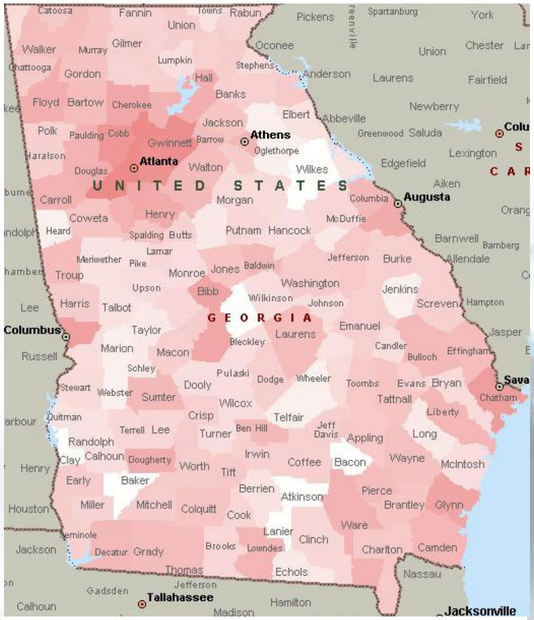


Figure shows projected disease spread of flu after 90 days (Keskinocak/Swann team)

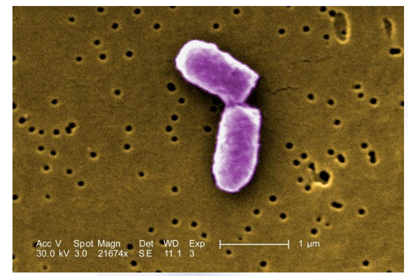
Influenza | Cholera | Guinea worm | Malaria | Polio

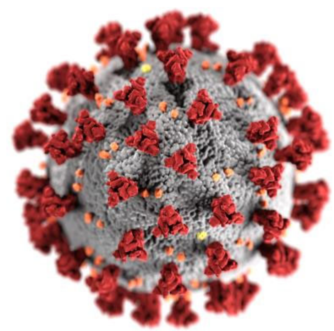
Infectious Disease Modeling

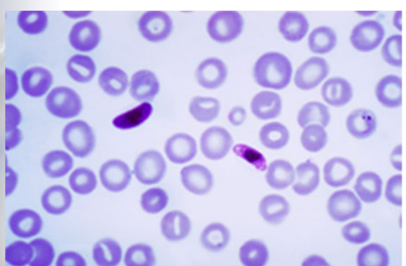
Disease progression in an individual – Natural history

→

Disease spread

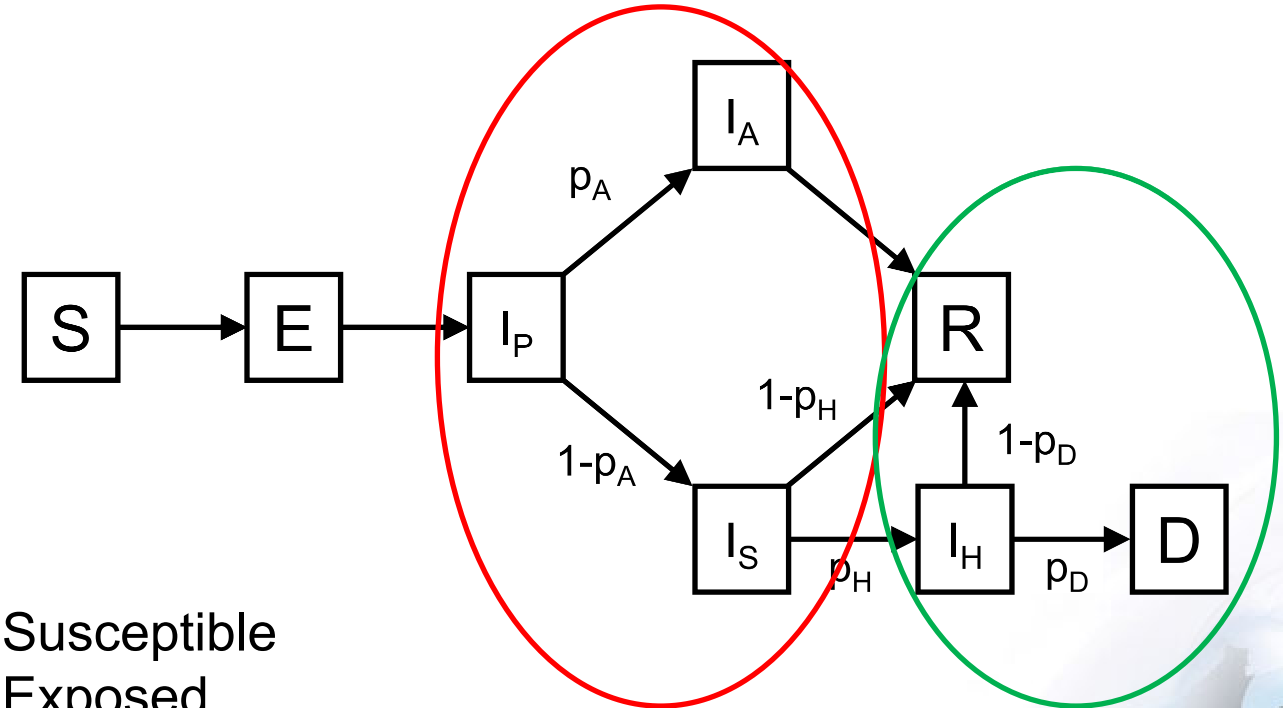






https://www.cdc.gov/media/subtopic/images.htm
https://www.cdc.gov/fungal/antifungal-resistance.html
https://en.wikipedia.org/wiki/Plasmodium_falciparum

Natural history – Example: Covid19



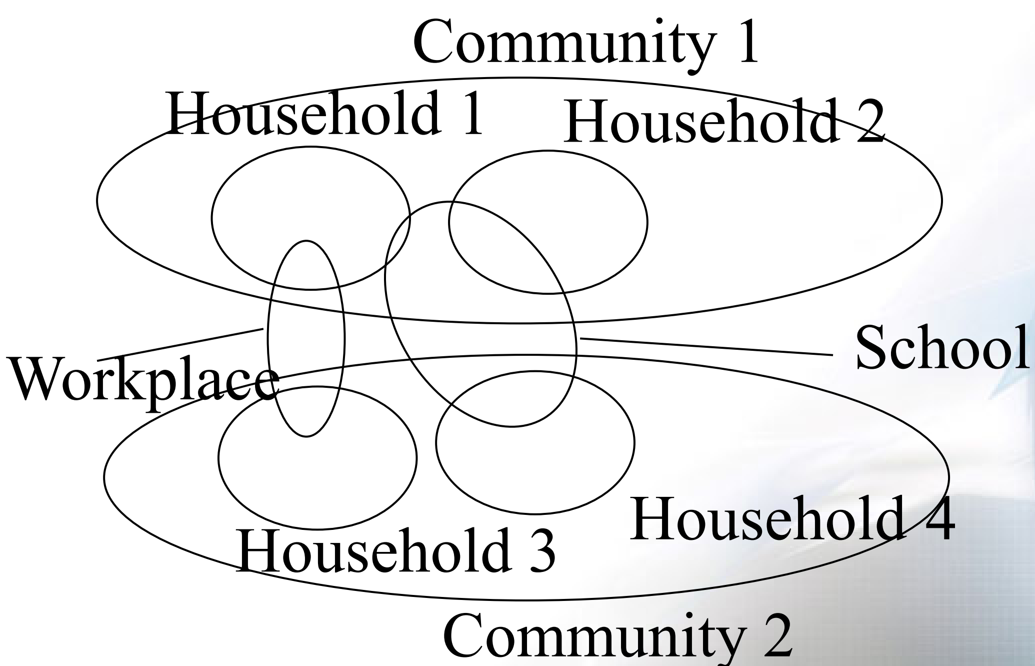
S: Susceptible
E: Exposed
I_P: Presymptomatic
I_A: Asymptomatic
I_S: Symptomatic
R: Recovered
I_H: Hospitalized
D: Dead

S-E-I-R

S-I-R

Disease spread – Example: Covid19

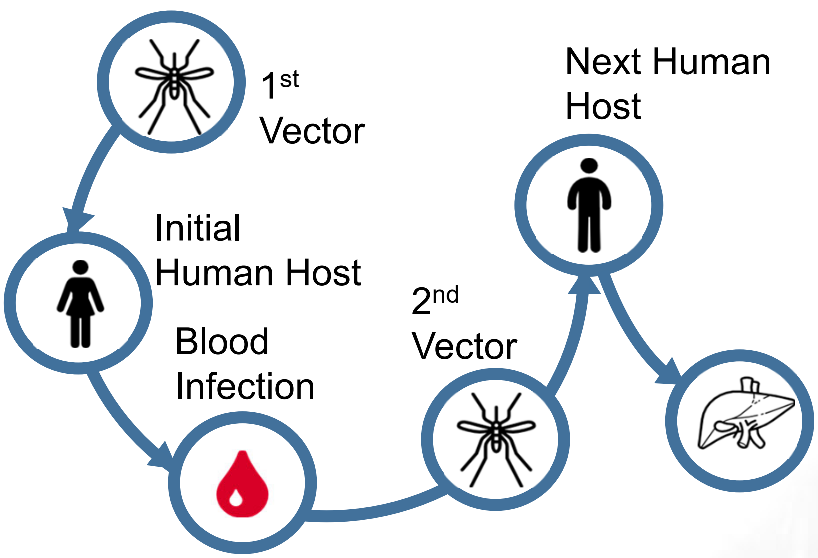
- Households
- Peer groups (e.g., workplace and schools)
- Community
- Household statistics, classroom sizes, age statistics
- Mobility & interaction patterns, e.g., workflow data



Disease spread - Transmission

- Human-to-human
  - Respiratory diseases (e.g., flu, Covid-19), STDs

- Vectors/Animals
  - Malaria, Guinea Worm



Disease spread – Example: Malaria

Mosquito

- Natural death rate
- Percent of the population that bites per day
- Duration in the incubation stage
- Probability of a mosquito contracting malaria from a human in the incubation and infection stage
- Probability of contracting malaria from an asymptomatic person
- …

Human

- Probability of contracting malaria from an incubating or infectious mosquito
- Duration in the incubation stage for each age group
- Probability of transitioning from slow recovery to immunity / fast recovery
- Lag from incubation to symptomatic, infectious
- Recovery rates
- …

- Environmental or other risk factors

Disease spread - Transmission

- Human-to-human
  - Respiratory diseases (e.g., flu, Covid-19), STDs
- Vectors/Animals
  - Malaria, Guinea Worm

Figure 1.20 Complex Life Cycle of *Dracunculus medinensis* (Guinea worm)

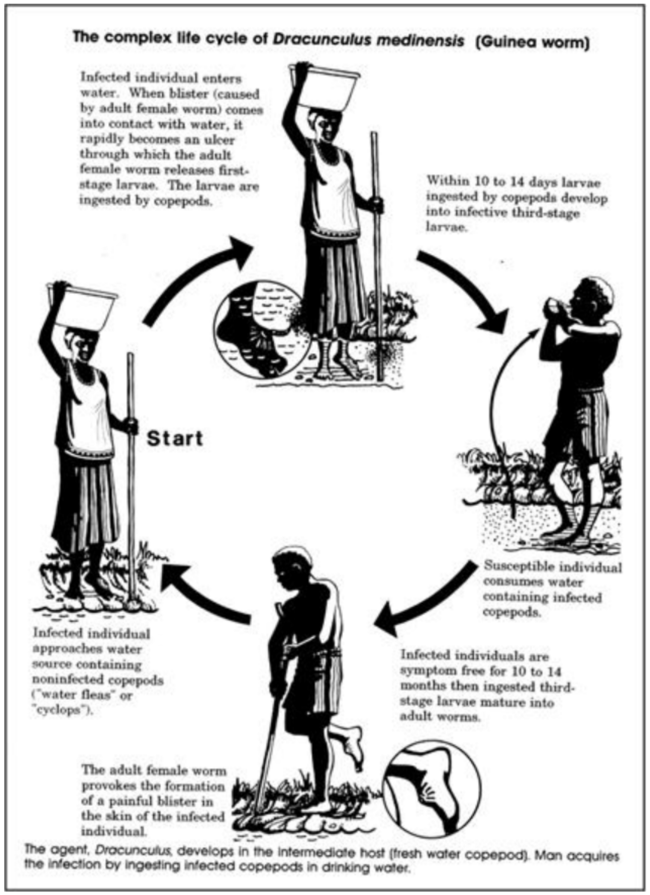
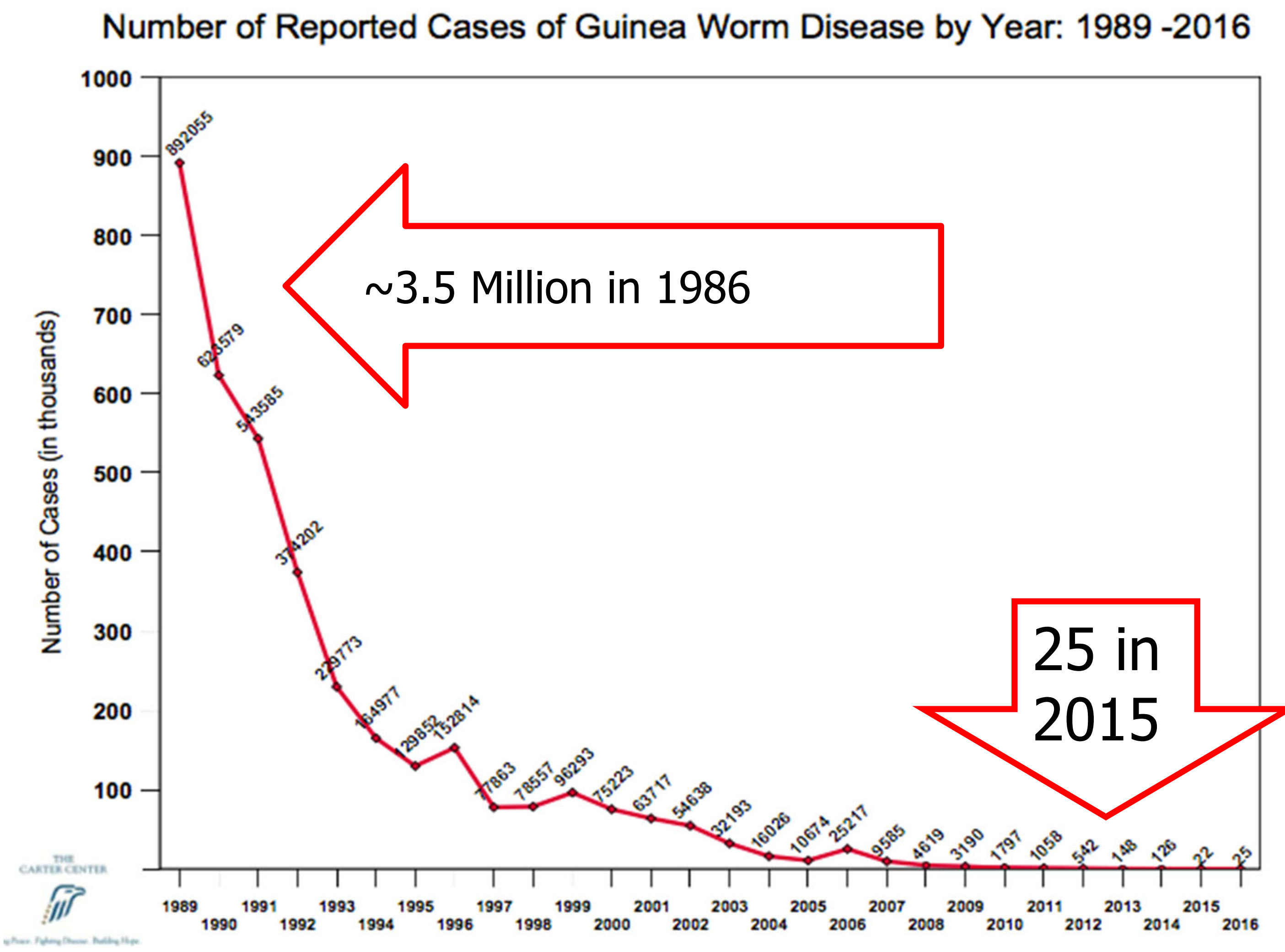


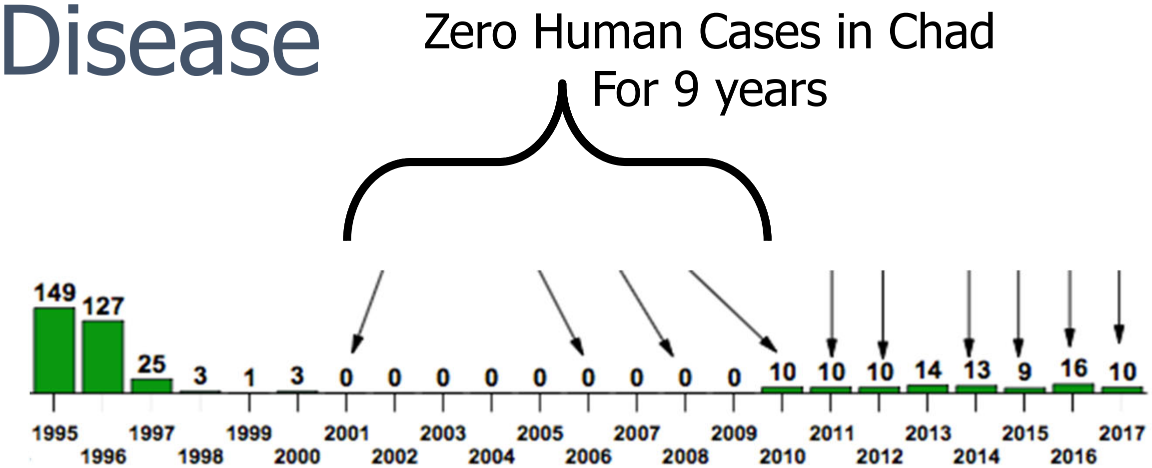
Image Description

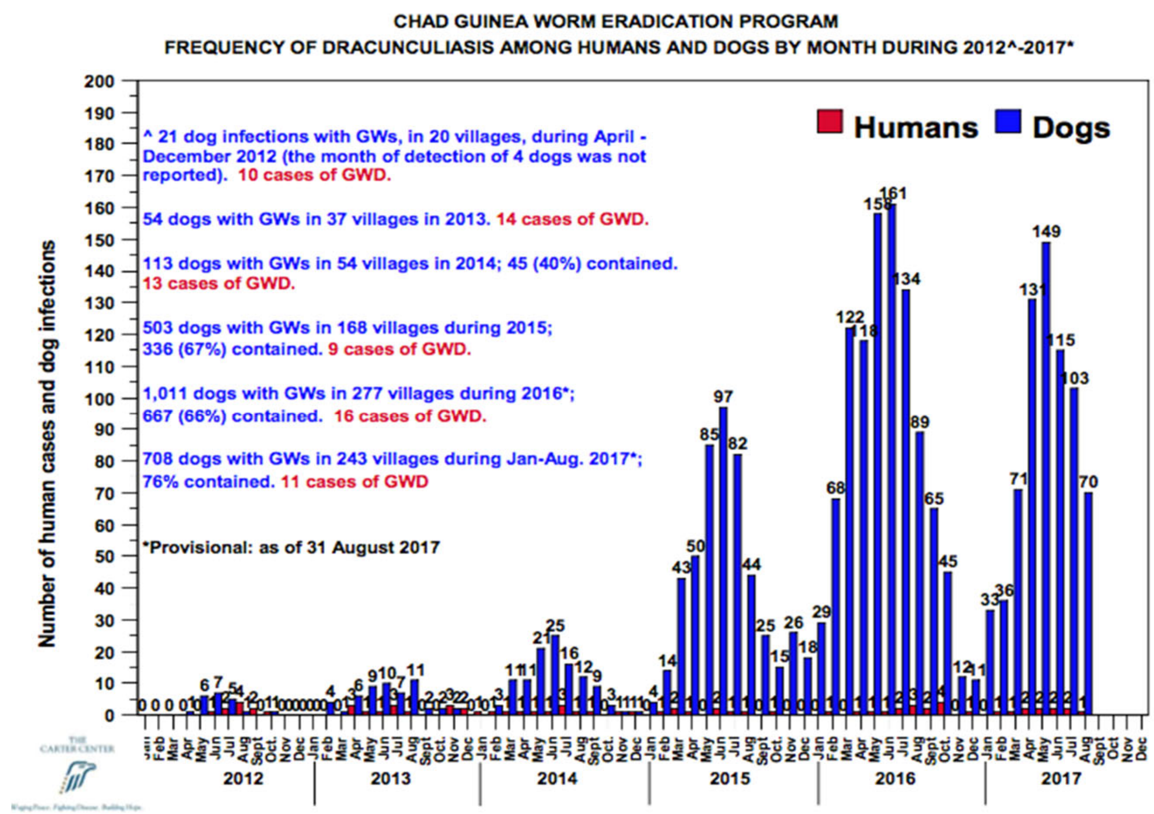
Source: Centers for Disease Control and Prevention. Principles of epidemiology, 2nd ed. Atlanta: U.S. Department of Health and Human Services;1992.

Guinea Worm Disease



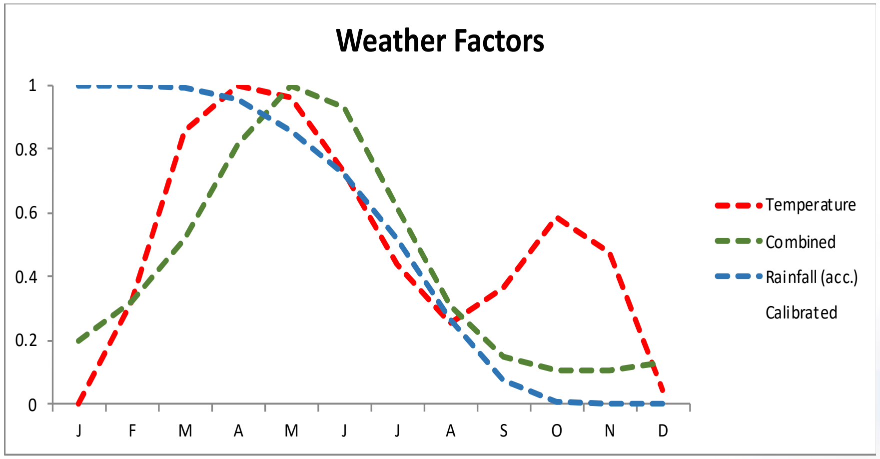
Guinea Worm Disease in Chad





Guinea Worm Transmission Model

- Agent-based model
- Environmental factors: temperature & rainfall → Worm burden in water → Rate of infection



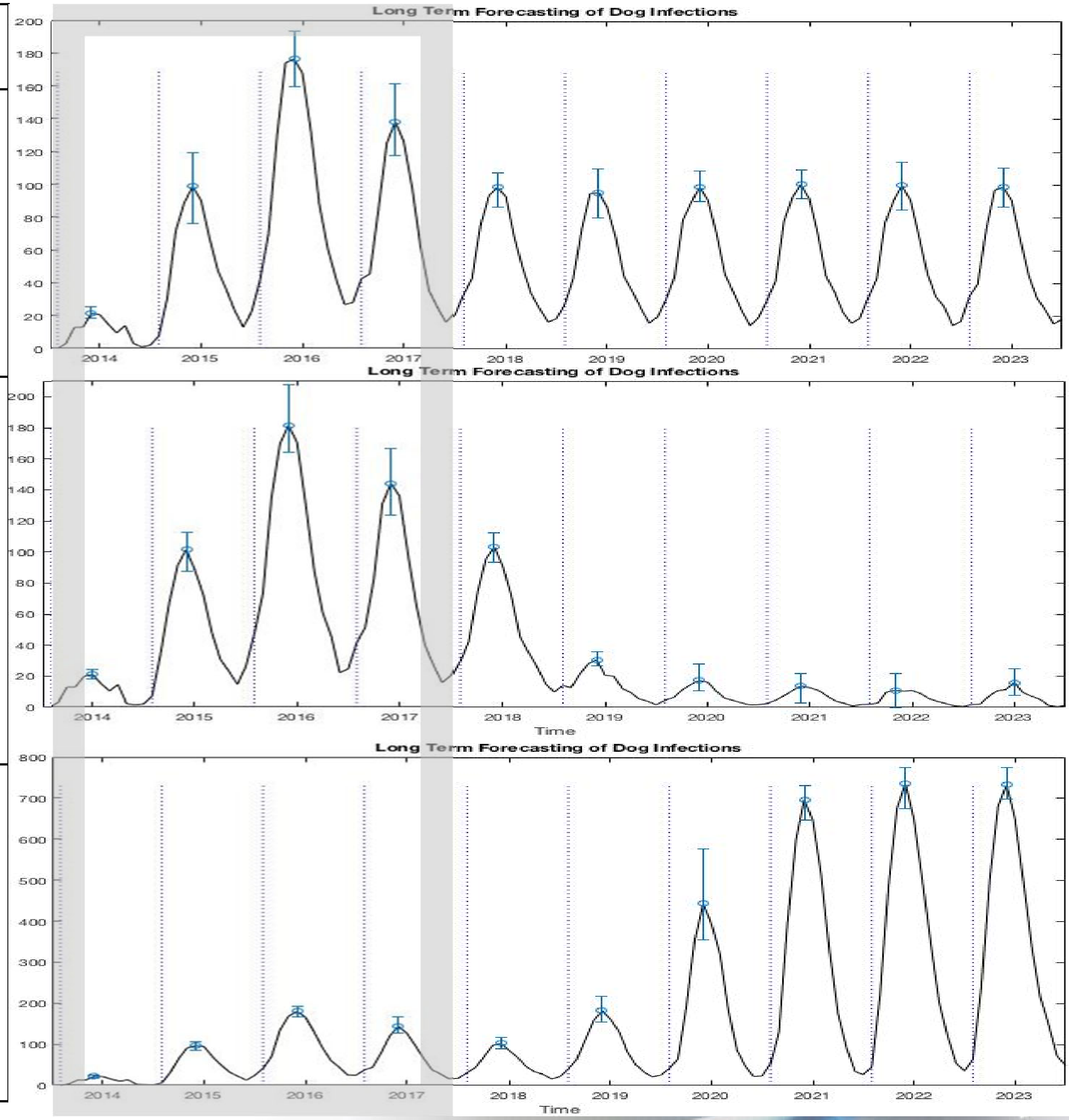
https://www.ajtmh.org/view/journals/tpmd/103/5/article-p1942.xml

ASTMH
THE AMERICAN JOURNAL OF TROPICAL MEDICINE AND HYGIENE
official Journal of the American Society of Tropical Medicine and Hygiene

Agent-Based Simulation for Seasonal Guinea Worm Disease in Chad Dogs

Tyler Perini [1], Pinar Keskinocak [1], Zihao Li [1], Ernesto Ruiz-Tiben [2], Julie Swann [1,3], and Adam Weiss [2]

Scenario:	*ABATE*	*Tether*	*Other*
Baseline	40%	76%	17%
Increased	70%	95%	17%
Decreased	20%	50%	17%

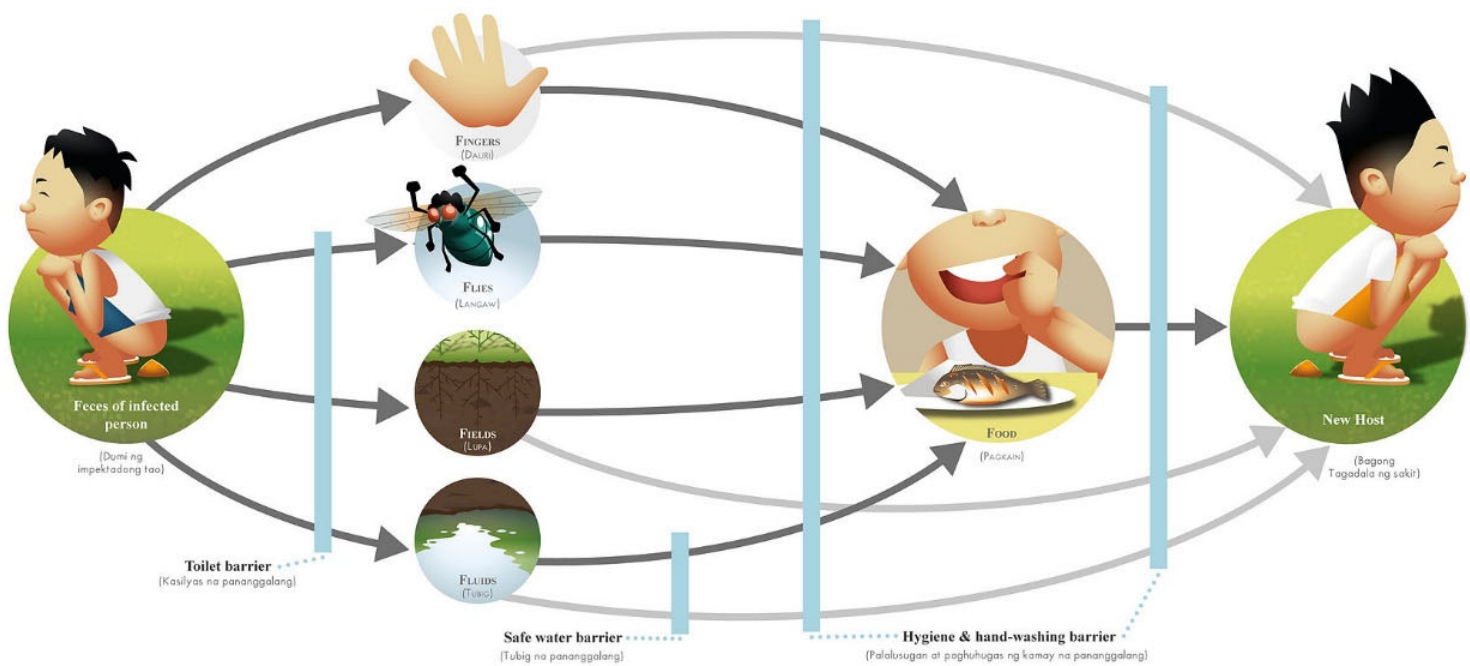


Disease spread - Transmission

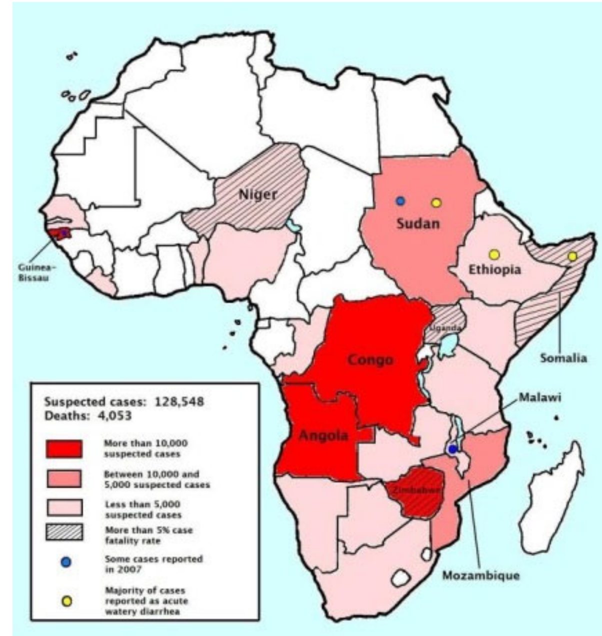
- Human-to-human
  - Respiratory diseases (e.g., flu, Covid-19), STDs
- Vector
  - Malaria, Guinea worm
- Vehicles
  - Cholera, typhoid fever, salmonella

Cholera Transmission

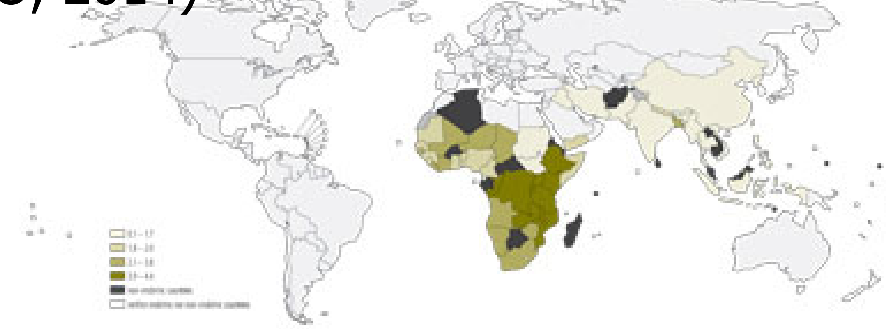
- Oral-Fecal Pathway
  - Five F’s: Feces, Fingers, Flies, Fields, Fluids, Food



Cholera Worldwide

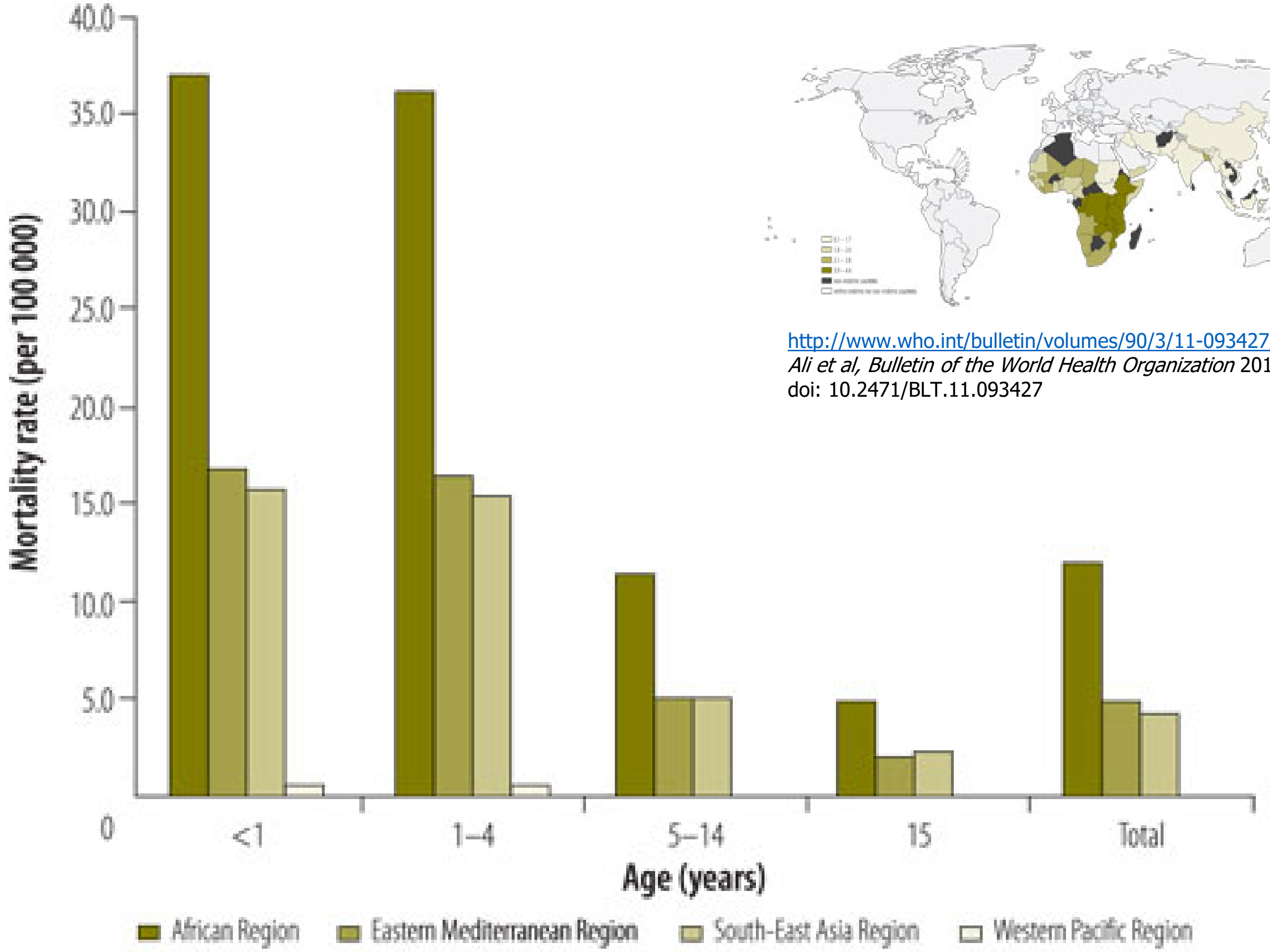


- 7 major pandemics in recorded history
- Many notable outbreaks since 1991. Examples:
  - 2008: Zimbabwe
  - 2010: Nigeria, Haiti, Dominican Republic
  - 2014: Ghana
- Cholera endemic in many places
- Overall, 1.4-4.3 million cases of cholera per year, leading to 28,000-142,000 deaths (WHO, 2014)



http://www.who.int/bulletin/volumes/90/3/11-093427/en/
Ali et al, Bulletin of the World Health Organization 2012;90:209-218A.
doi: 10.2471/BLT.11.093427

Cholera Impact - Incidence (new cases) of disease and mortality differ by age



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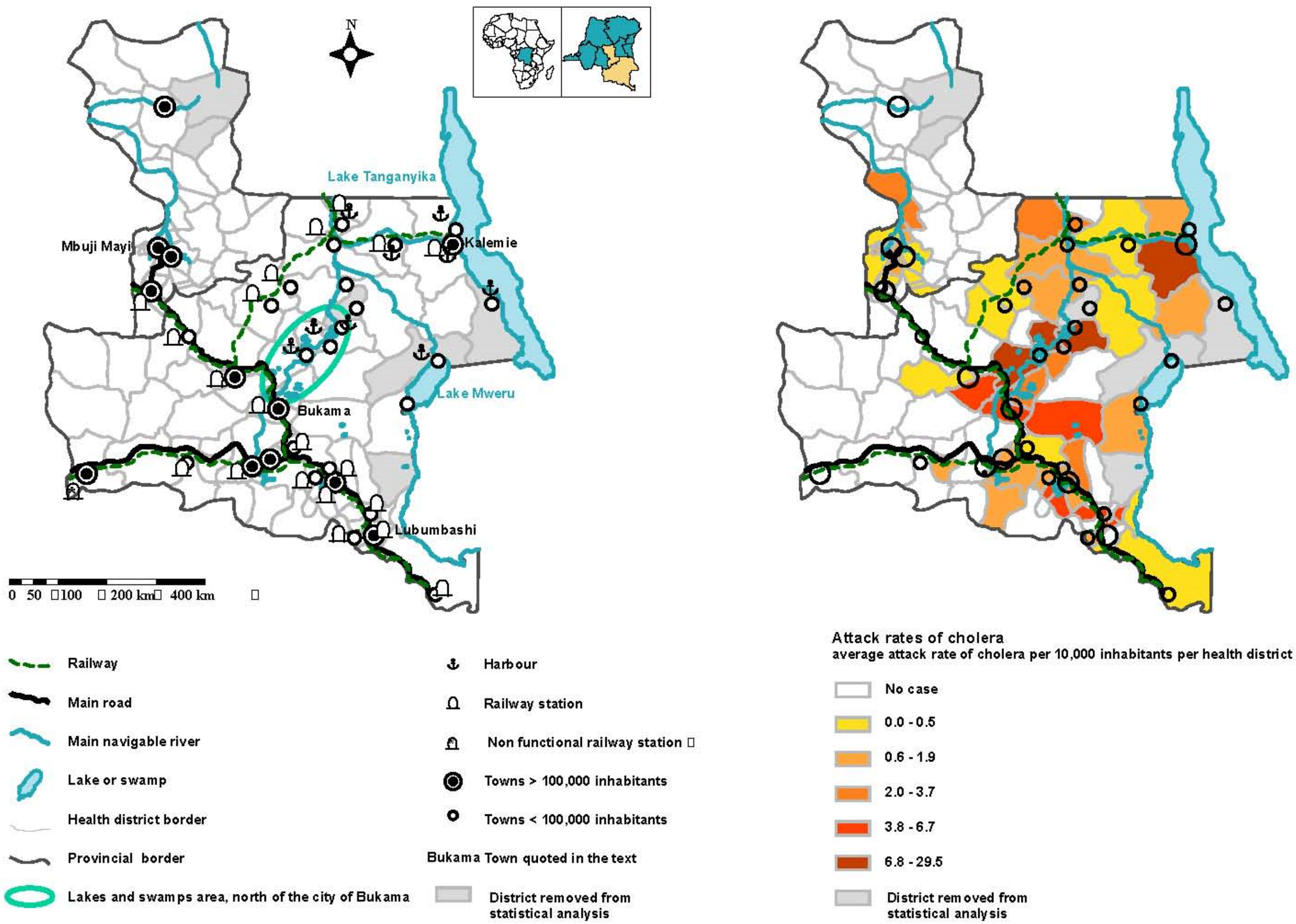
Ali et al, Bulletin of the World Health Organization 2012;90:209-218A.

doi: 10.2471/BLT.11.093427

Ali et al (2012), “The global burden of cholera”

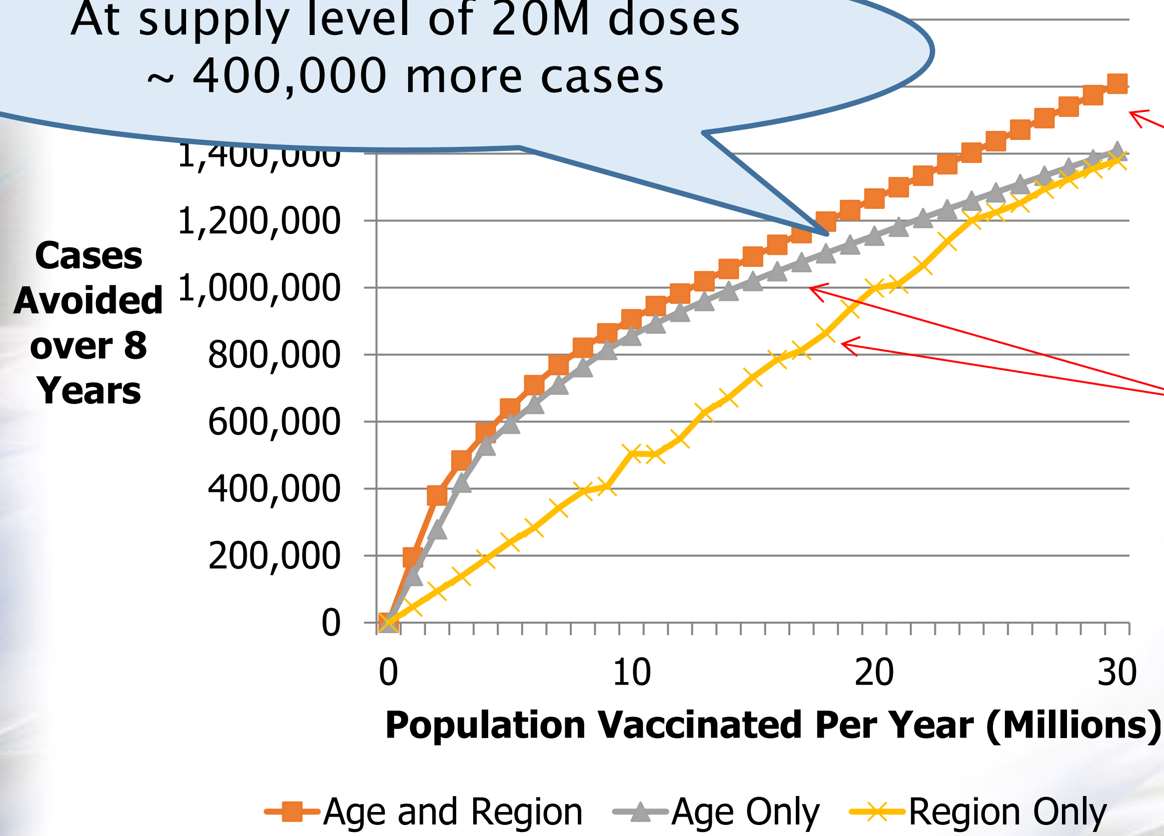
Environmental or other risk factors



Piarroux et al (2009), The journal of field actions. (Democratic Republic of Congo)

Resource allocation – Example: Oral cholera vaccine

At supply level of 20M doses
~ 400,000 more cases



Targeting groups by age and region is the best strategy.

Simply targeting primarily the high-risk region, or children (who have the highest risk) is less effective.

H.K. Smalley, P. Keskinocak, J. Swann, A. Hinman (2015), "Optimized Oral Cholera Vaccine Distribution Strategies to Minimize Disease Incidence: A Mixed Integer Programming Model and Analysis of a Bangladesh Scenario," *Vaccine*, Vol.33, No.46, 6218–6223.

Our Contribution

- Optimize OCV distribution policies to determine the best OCV allocation strategy to minimize cases or deaths:
  - Differentiate groups by age AND region, with varying risk levels
  - Consider fixed and varying vaccine efficacies based on age and years since vaccination
- Quantify cost-effectiveness of strategies

- J. Ahmed, P. K. Bardhan, W. Carter, L. Gonzalez, R. Hall, J. Heeger. L. Ivers, A. Khan, P. Keskinocak, H. Matzger, M. Mengel, D. Nazzal, C. Paradiso, F. Qadri, D. Sack, M. Villareal, S.A. Zahan (2013), "Comprehensive Integrated Strategy for Cholera Prevention and Control," Coalition for Cholera Prevention and Control, August. http://choleracoalition.org/resources/

CCPC COALITION FOR CHOLERA PREVENTION & CONTROL

- P. Keskinocak, D. Nazzal, M. Villarreal (2013), "Procurement and Logistics," Meeting of the Coalition for Cholera Prevention and Control, National Institutes of Health, Bethesda, MD, June 3-4.
- H.K. Smalley, P. Keskinocak, J. Swann, A. Hinman (2015), "Optimized Oral Cholera Vaccine Distribution Strategies to Minimize Disease Incidence: A Mixed Integer Programming Model and Analysis of a Bangladesh Scenario," *Vaccine*, Vol.33, No.46, 6218–6223.

Examples of Interventions

- Pharmaceutical
  - Vaccines, antivirals
- Non-pharmaceutical
  - School closures, Travel restrictions, Physical distancing (e.g., voluntary quarantine), Age-based restrictions, …
- Combined strategies: Testing, tracing, isolation
- Behaviors/Compliance (geographically, over time, subpopulations)
- How, where, when to allocate limited resources?

Infectious Disease Modeling

Disease progression in an individual – Natural history → Environment / Interventions / Behaviors → Disease spread

- Metrics/outcomes of interest (by age group, geographically, subpopulation, etc.)
  - New infections per time period, e.g., daily
  - Timing and magnitude of the "peak"
  - Total number of infections or % of population infected (IAR)
  - Number or % hospitalized or dead
  - Resource needs (e.g., hospital beds, ventilators)

COVID19 MODELING AND EVALUATING INTERVENTION STRATEGIES

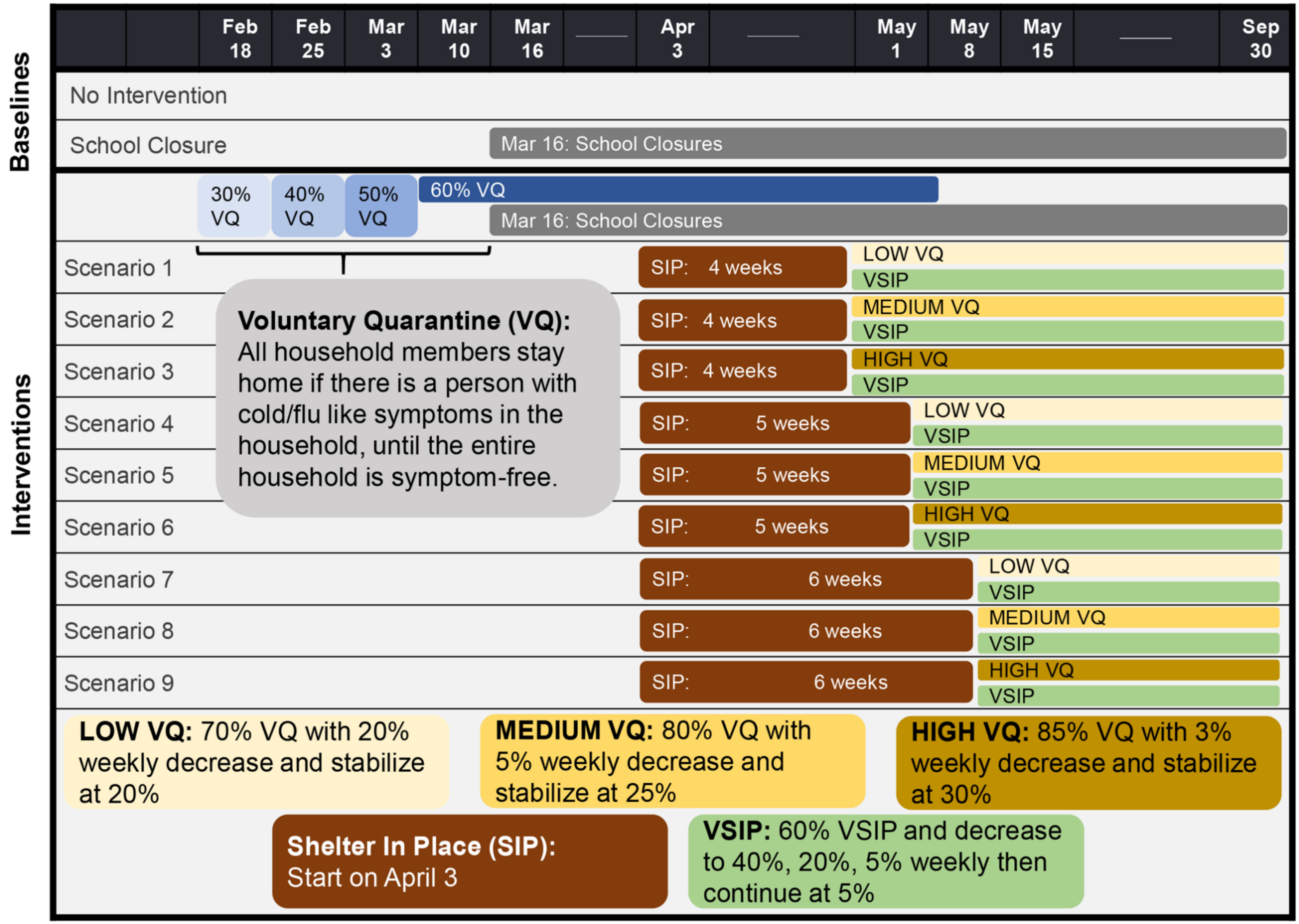
Collaborators include: John Asplund, Ph.D.; Emma Baubly; Arden Baxter; Saurabh Doodhwala; Akane Fujimoto; Daniel Kim; Dima Nazzal, Ph.D.; Buse Eylul Oruc; Pelin Pekgun, Ph.D., Lauren Steimle, Ph.D.; Tyler Perini; Josh Rosenblum; Erik Rosenstrom; Nicoleta Serban, Ph.D.; Melody Shellman; Chris Stone; Julie Swann, Ph.D.; Inci Yildirim, MD, Ph.D.; April Yu; Georgia Tech Institute for People and Technology; GA Department of Public Health

Funding: "Integrated Systems Model to Inform State and Local Planning for the COVID-19 Pandemic," Council of State and Territorial Epidemiologists (CSTE); RADx Underserved Populations (RADx-UP) program

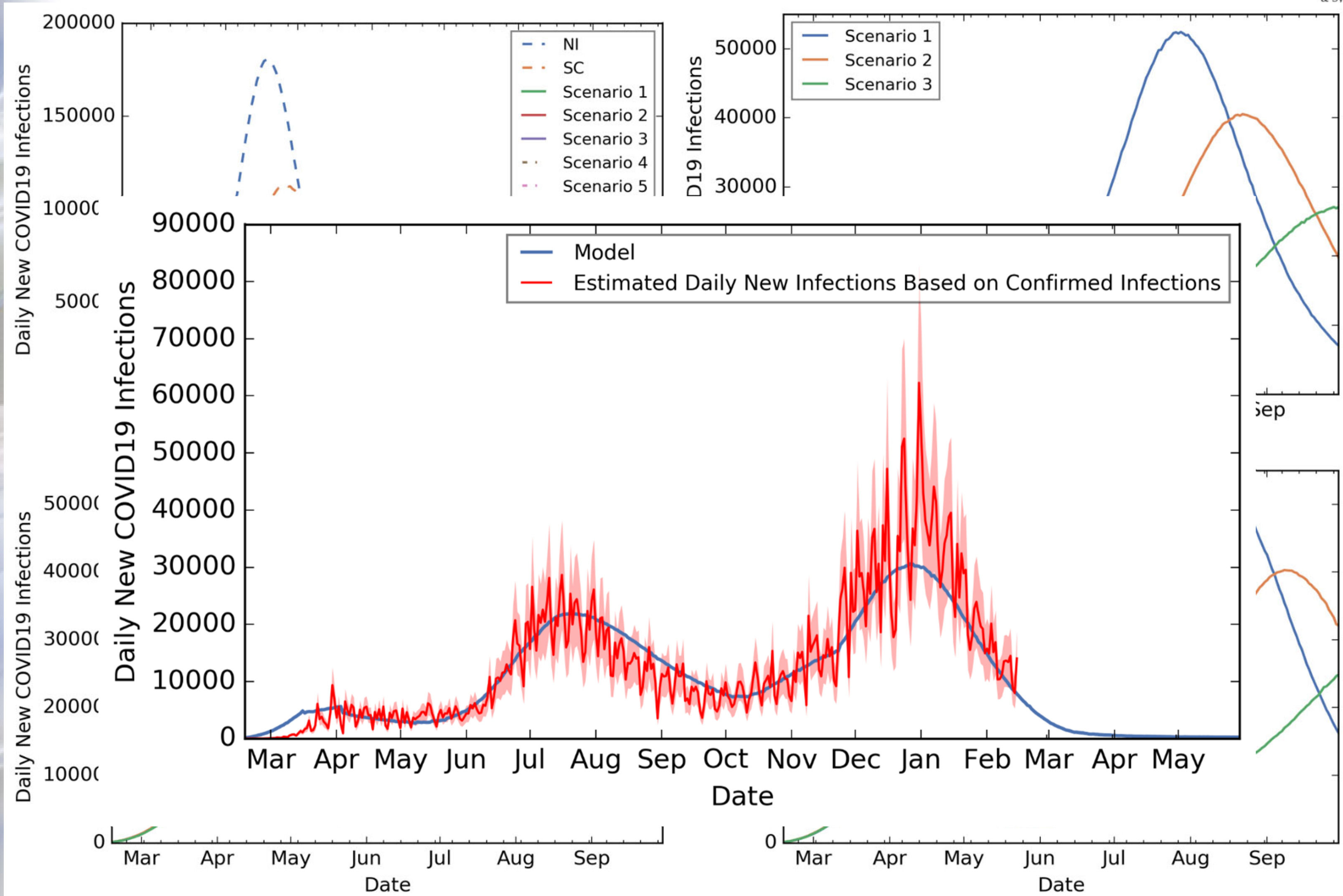
Research insights

- Modeling the disease spread → Projections
- Evaluating the impact of interventions
  - School closures, Shelter-in-place, voluntary-quarantine
- Estimating resource needs
- Impact of interventions on society: "homebound days" versus reduction in disease spread
- Impact of testing/isolation depending on compliance
- Vaccine allocation – Benefits of serology testing?
- Tradeoff between vaccine efficacy versus reach
- …

SCENARIOS FOR PHYSICAL DISTANCING

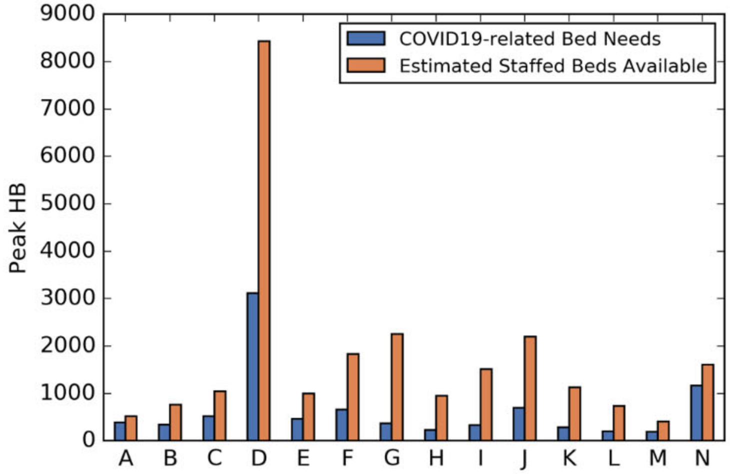


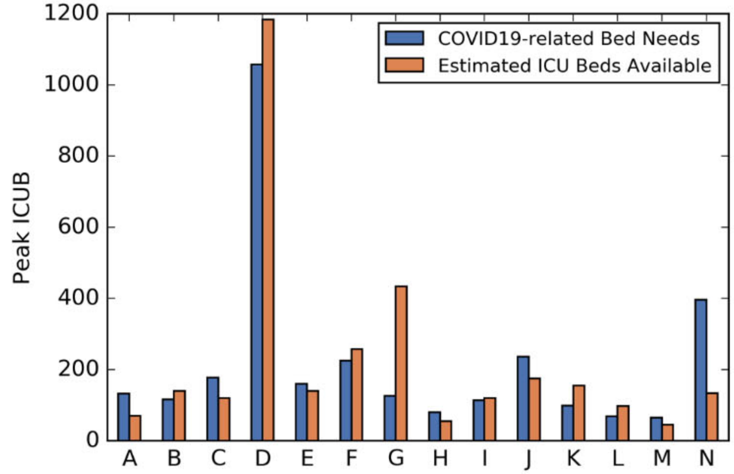
Daily new infections Projections In Georgia

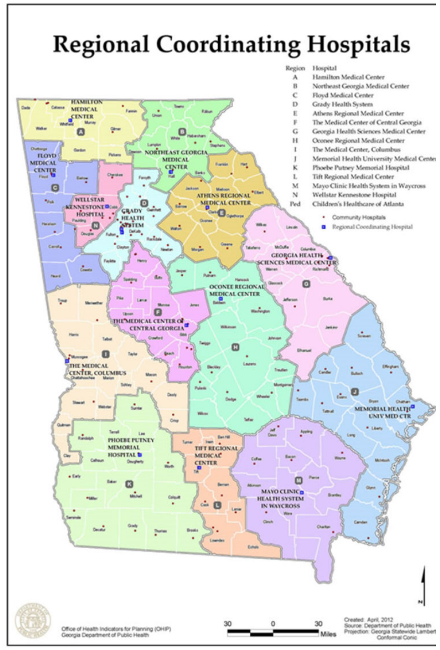


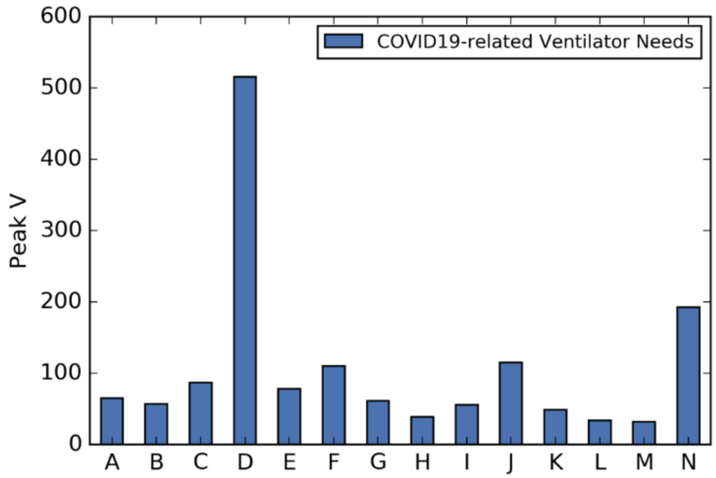
https://journals.plos.org/plosone/article/authors?id=10.1371/journal.pone.0239798

Healthcare resource estimation









WABE Where ATL meets NPR

"You may build all the ICUs you want. You may have all the ventilators you need. But you will not have the staff you need," del Rio said. "There simply are not enough ICU nurses or ICU doctors to take care of the patients."

Research questions

- Modeling the disease spread
- Evaluating the impact of interventions
  - School closures & reopening, Shelter-in-place, voluntary-quarantine
- Impact of interventions on society: "homebound days" versus reduction in disease spread
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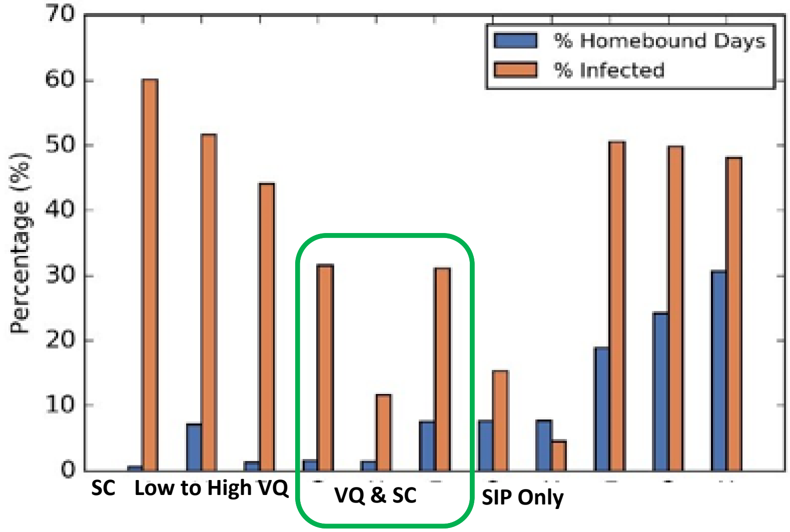
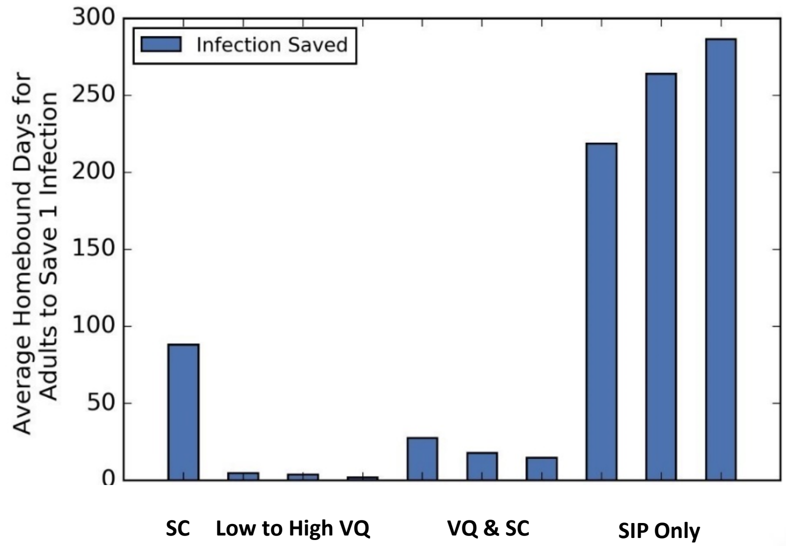
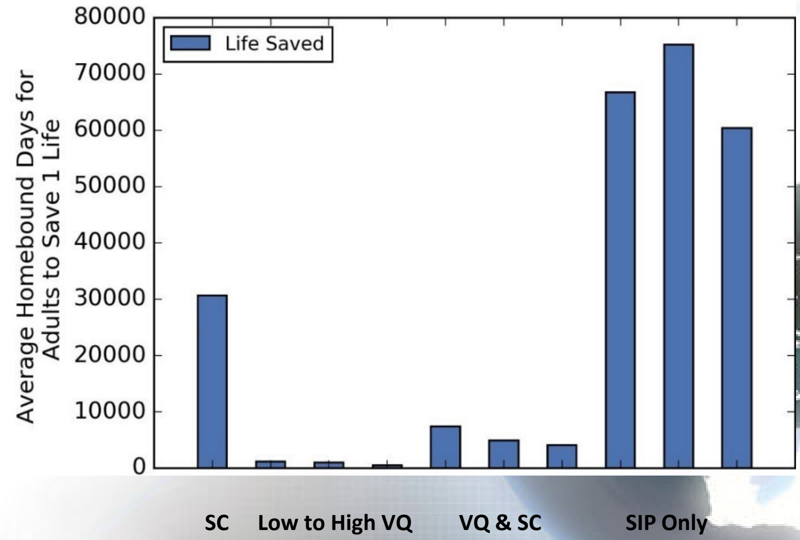
Health, society, economy, etc. – complex tradeoffs







https://bmcpublichealth.biomedcentral.com/articles/10.1186/s12889-021-10725-9

Research insights

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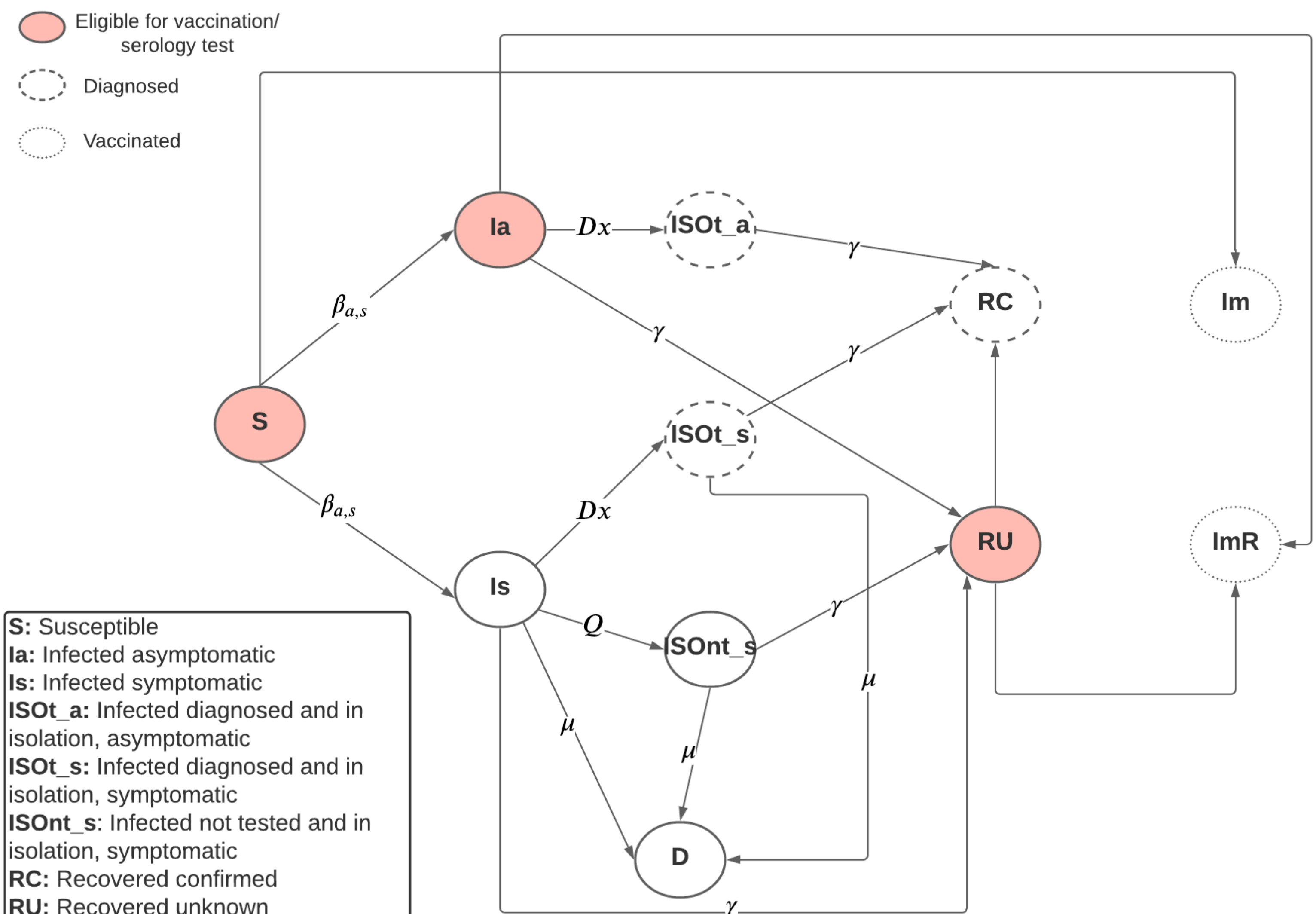
https://www.sciencedirect.com/science/article/pii/S0264410X21008288?via%3Dihub



S: Susceptible
Ia: Infected asymptomatic
Is: Infected symptomatic
ISOt_a: Infected diagnosed and in isolation, asymptomatic
ISOt_s: Infected diagnosed and in isolation, symptomatic
ISOnt_s: Infected not tested and in isolation, symptomatic
RC: Recovered confirmed
RU: Recovered unknown
Im: Immunized not previously infected
ImR: Immunized previously infected
D: Dead

Vaccine, Volume 39, Issue 35, 16 August 2021, Pages 5055-5063
https://www.sciencedirect.com/science/article/pii/S0264410X21008288?via%3Dihub

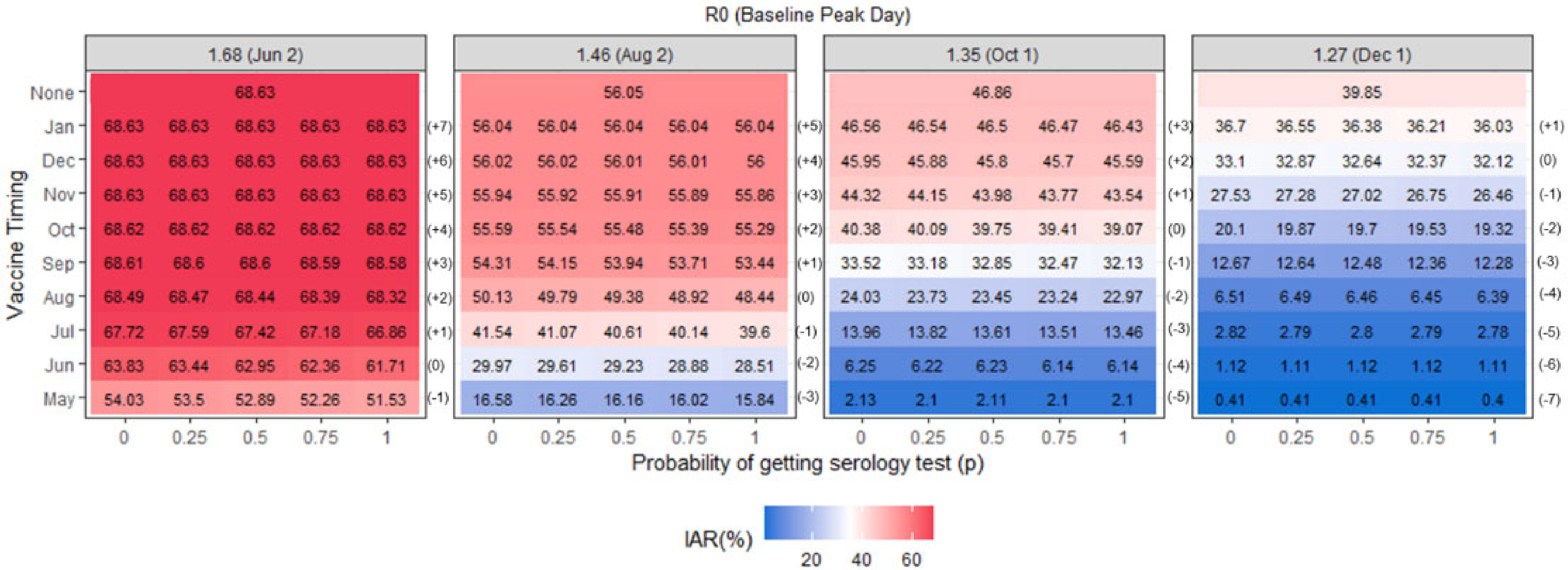


Figure 2: *Infection attack rate* for the scenarios evaluated when the vaccine is available for 50% of the population and the vaccine efficacy is 90%.

- Highest IAR: High R0 and vaccination available after the peak.
- Impact of serology test highest when the vaccines are deployed close to the peak time

Research insights

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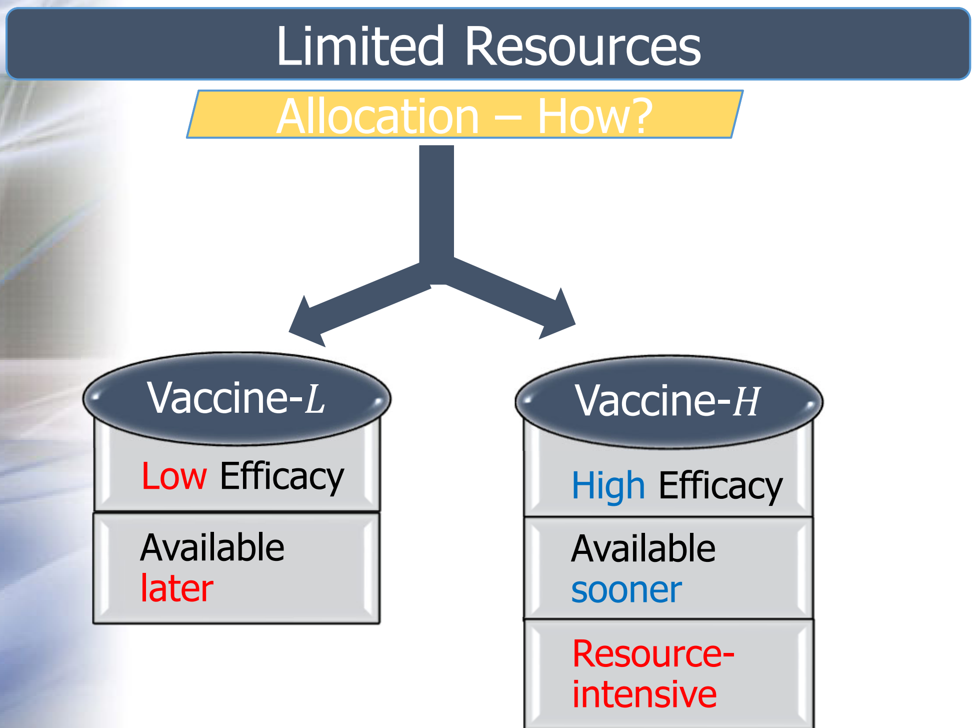
Tradeoffs between vaccine efficacy and reach



Reach of a vaccine

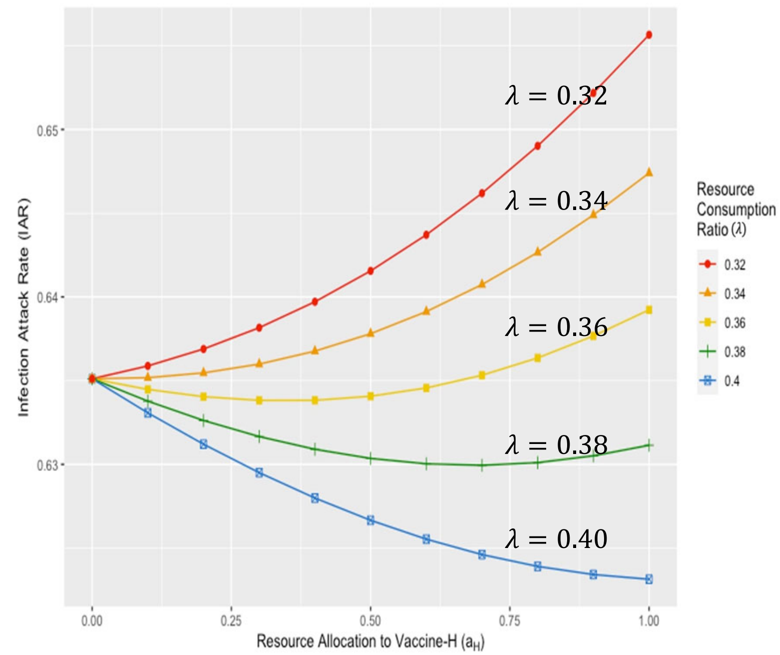


Figure 1 : IAR w.r.t. the percentage of resources allocated to vaccine-H

> Vaccine. 2021 Oct 18;S0264-410X(21)01346-3. doi: 10.1016/j.vaccine.2021.10.025.
Online ahead of print.

Resource allocation for different types of vaccines against COVID-19: Tradeoffs and synergies between efficacy and reach

Daniel Kim [1], Pelin Pekgün [2], İnci Yildirim [3], Pınar Keskinocak [4]

Research insights

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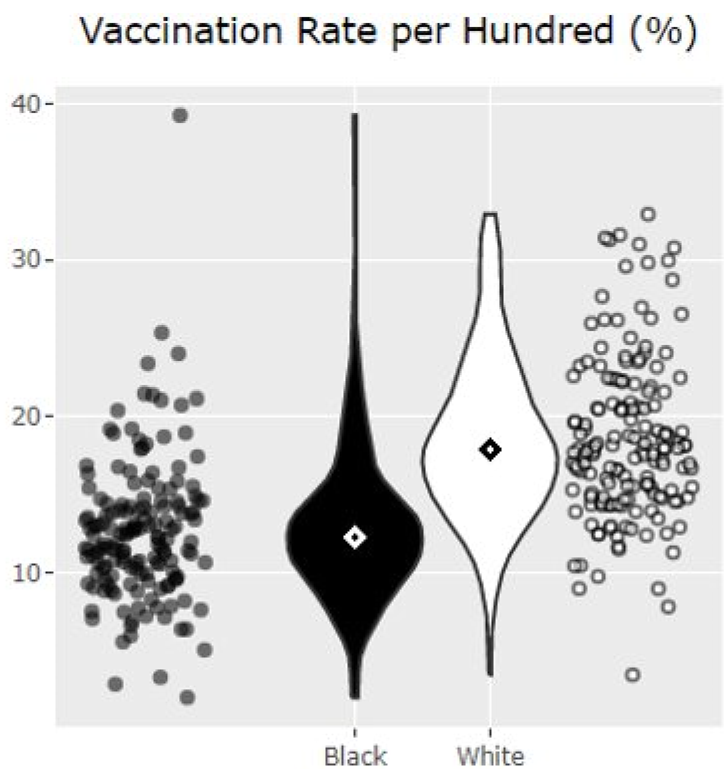
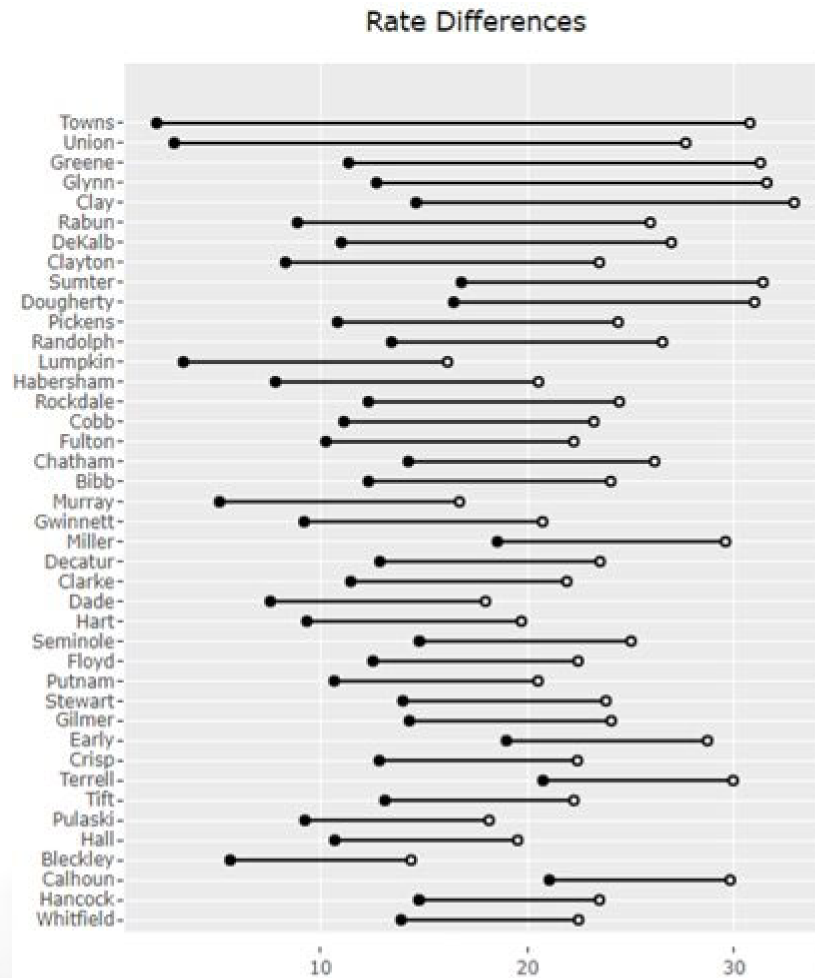
- Vaccine allocation – Benefits of serology testing?
- Tradeoff between vaccine efficacy versus reach
- Dashboards

Dashboards https://chhs.gatech.edu/covid19-dashboard

$$\frac{\text{Number of people vaccinated in subpopulation}}{\text{Total number of people in subpopulation}} \times 100$$





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