Modeling Parental Acceptance of Vaccination for Paediatric Infectious Diseases*

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* Based on joint work with Professor Chris T. Bauch (University of Waterloo). Published in Proc. R. Soc. B (2014).

Outline

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1. Vaccination as a disease control measure
2. Mathematical models of vaccine acceptance
3. Modeling vaccine uptake with group pressure
4. Estimation of parameters and model analysis
5. Conclusion

Vaccination

- Vaccination provides **direct** protection to vaccinated individuals, against smallpox, polio, measles, influenza ...
- And also provides **indirect** protection to non-vaccinated individuals, by decreasing transmission in the population (herd immunity).
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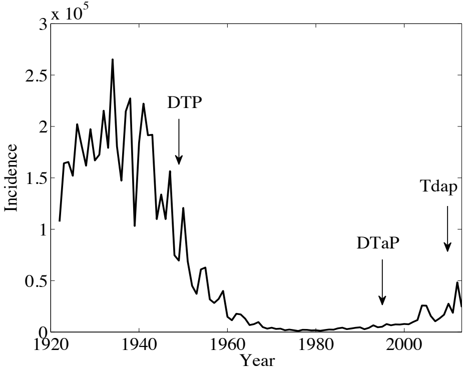
Pertussis Vaccination

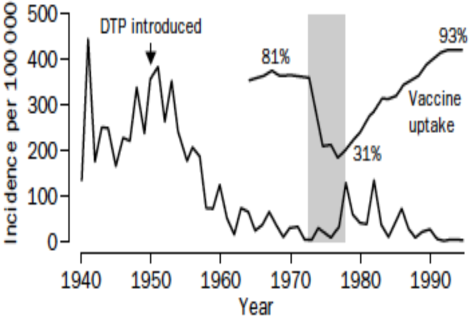
US pertussis incidence (data source: CDC).



- DTP: diphtheria-tetanus- whole cell pertussis vaccine.
- DTaP: diphtheria-tetanus acellular pertussis vaccine.
- Tdap or dTap: tetanus and reduced diphtheria-acellular pertussis vaccine.

Vaccine Scares

UK pertussis incidence and vaccine uptake



[Lancet 351, 1998]

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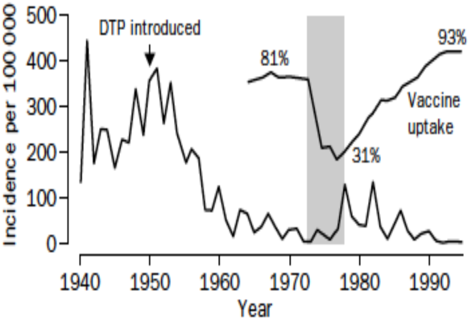


Vaccination is non-mandatory.

[Lancet 351, 1998]

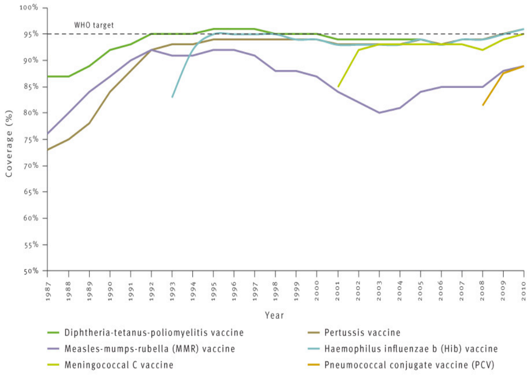
Outline

Vaccination Models

- Bauch and Earn (2004).
- Bauch (2005).
- Shim et al. (2011).
- Wu et al. (2011).
- Bauch and Bhattacharyya (2012).

Childhood Immunization

Annual vaccination coverage at 24 months, England, 1987–2010



WHO: World Health Organization.
MMR replaced single measles vaccine in 1988. Hib vaccine was introduced in 1992, meningococcal C vaccine in 1999 and PCV in 2006.

[Euro Surveill,17(16), 2012]

Herd Immunity Threshold (HIT)

- The basic reproduction number (R_0) is the average number of secondary infections due to the introduction of an infectious individual in a completely susceptible population.
- If $R_0 < 1$ then the epidemic will die out; if $R_0 > 1$ then there is a chance it will be endemic.
- If $R_0 > 1$, the Herd Immunity Threshold

$$\text{HIT} = 1 - \frac{1}{R_0}.$$

- For pertussis, $R_0 = 18$ and so HIT $\simeq 95\%$.

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Vaccination Models Explaining the High Level Acceptance Rates

- Altruism – Shim et al. (2012), Vietri et al. (2012), Chapman et al. (2012).
- Public health messaging – d'Onofrio et al. (2012).

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Objective

- Find a model of parental vaccinating behaviour for paediatric infectious diseases to better explain the whole range of observed vaccinating behaviour, including both vaccine refusal, and the high vaccine coverage levels so commonly observed.

- Validate that model by fitting it to real data.

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Health Belief Model

Health Believe Model

- Personal variables
  1. Parental perceived risk of infection in terms of susceptibility and severity.
  2. Perceived risk of vaccination.
  3. Vaccine efficacy.
  4. Vaccine cost and accessibility.

- Social variables

  Social norms and group pressure.

[J Dev Behav Pediatr, 26, 441–452, 2005]

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Social Norms

- Social norms are informal non-coded rules that are invoked by groups, e.g. ethnic, religious; and non-conformity to which might be faced with sanctions, ranging from verbal to physical, e.g. by maligning, ostracizing, etc., that can be interpreted by the group members as a pressure to conform
- Social norms: prescriptive or proscriptive
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Payoff Function – Benefit *vs.* Cost

Two strategies: Vaccinate (V) or Not to vaccinate (N) with payoffs

- $\pi(N) = H - r_i$

H: full-health gain
r_i: perceived risk of infection

- $\pi(V) = H - r_v$

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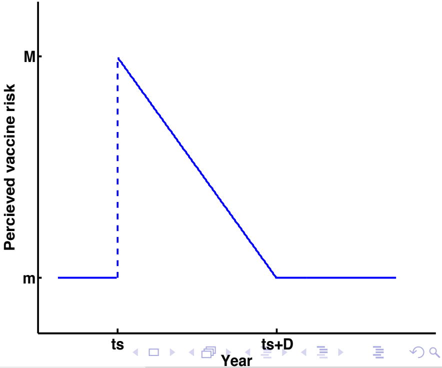

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m: perceived magnitude of risk before the year t_s
$\sigma := M/m$: relative risk at the year t_s
D: length of the decay period of risk perception

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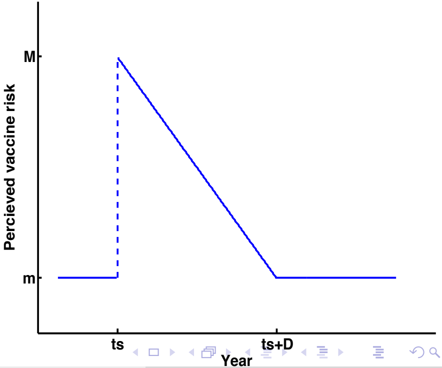

Payoff Function – Benefit *vs.* Cost

Two strategies: Vaccinate (V) or Not to vaccinate (N) with payoffs

- $\pi(N) = H - r_i + \delta_0 (1 - x)$

H: full-health gain
r_i: perceived risk of infection
$r_i(t) = \alpha I(t)$
δ_0: group pressure
x: proportion of vaccinators

- $\pi(V) = H - r_v + \delta_0 x$

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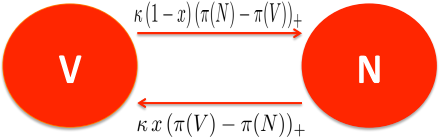
Imitation Dynamics



κ: imitation rate
V: vaccination strategy adopted by a proportion x with a payoff $\pi(V)$
N: no-vaccination strategy adopted by a proportion $1-x$ with a payoff $\pi(N)$

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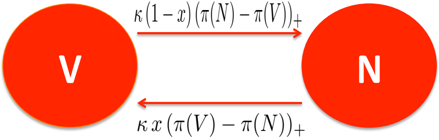

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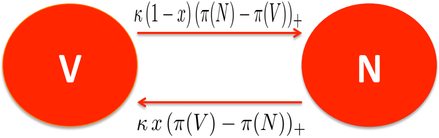

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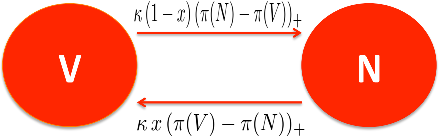

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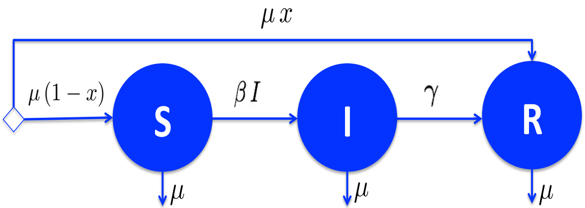
$$\frac{dx}{dt} = \kappa'\, x\,(1-x)\,[-\omega + I + \delta\,(2x-1)] \qquad \text{(B)}$$

Susceptible-Infected-Removed (SIR) Model



S: susceptible density
I: infected density
R: removed density
$S + I + R = 1$

μ: birth/death rate
β: disease transmission rate
γ: recovery rate
x: proportion of vaccine acceptors

[PLoS Comput Biol, 8 e1002452, 2012]

Susceptible-Infected-Removed (SIR) Model

$$\left.\begin{aligned}\frac{dS}{dt} &= \mu(1-x) - \beta S I - \mu S\\ \frac{dI}{dt} &= \beta S I - (\mu+\gamma) I\\ \frac{dR}{dt} &= \mu x + \gamma I - \mu R\end{aligned}\right\} \qquad \text{(D)}$$

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Remark:

- If $x = 0$ then $R_0 = \dfrac{\beta}{\mu + \gamma}$.
- If x is a fixed proportion then $R_n = R_0\,(1 - x)$, which leads to the HIT.

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Coupled Disease-Behavioral Model

$$\left.\begin{aligned}
\frac{dS}{dt} &= \mu\,(1-x) - \beta\,S\,I - \mu\,S \\
\frac{dI}{dt} &= \beta\,S\,I - (\mu+\gamma)\,I \\
\frac{dx}{dt} &= \kappa'\,x\,(1-x)\,\left[-\omega + I + \delta\,(2\,x-1)\right]
\end{aligned}\right\} \qquad \text{(DB)}$$

Outline

Fitting data to model

Data and methods

- Data: Pertussis vaccine coverage and pertussis incidence in the UK, from 1967–2010.

- Fitting procedures:
  - Fit (full) model with social norm and (nested) model without social norm.
  - Parameter estimation using method of nonlinear least squares.
  - Fix $R_0 = 18$, $\mu = 1/50\, y^{-1}$, and $\gamma = 365/22\, y^{-1}$.

Fitting data to model

Model selection

- Corrected Akaike information criterion

$$\mathrm{AIC}_c = -2\,\log(L_{\max}) + 2\,\ell + \frac{2\,\ell\,(\ell+1)}{n-\ell-1}$$

n: number of data points
ℓ: number of fitted model parameters

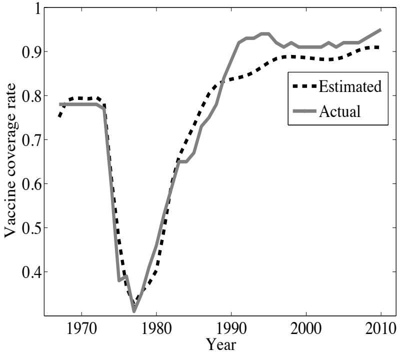
$$L_{\max} = \left(2\,\pi\,e^1\,\mathrm{RSS}/n\right)^{-n/2}$$

RSS: residual sums of squares

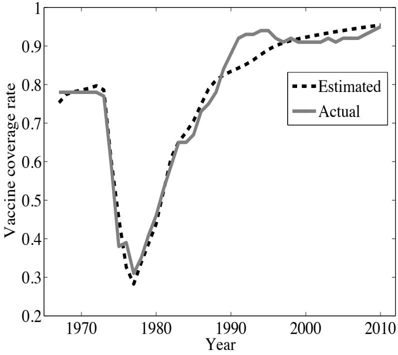
Fitting data to model

Best fit curves

Without social norm (nested)



With social norm (full)



Fitting data to model

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Without social norm (nested)

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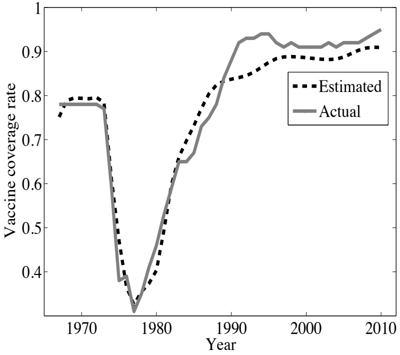

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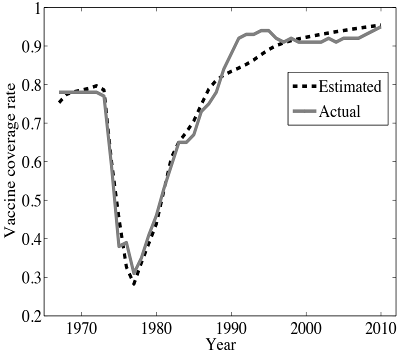

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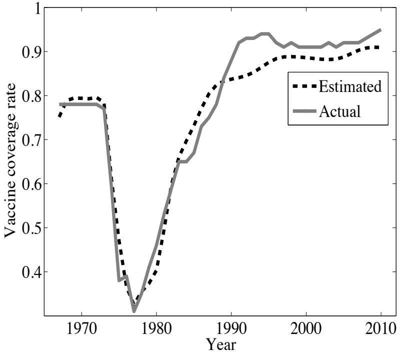

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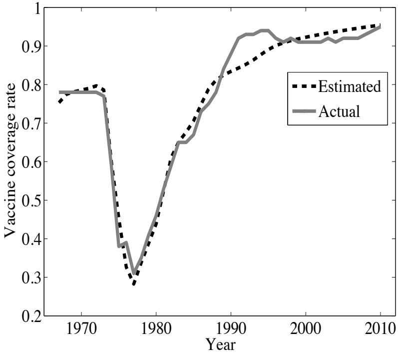

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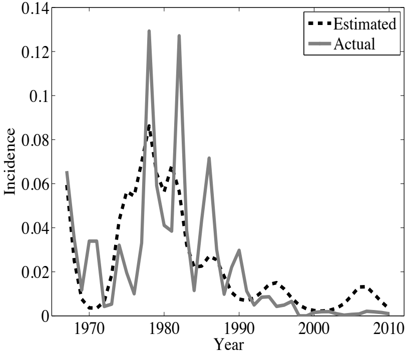

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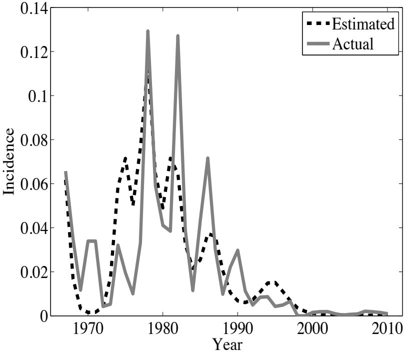

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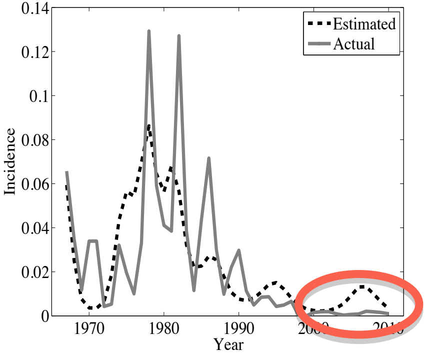

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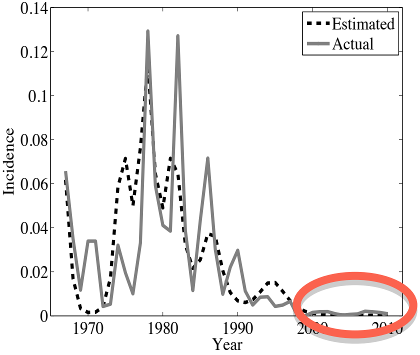

Model equilibria

Disease-free equilibria

When perceived risk of vaccination is constant ($\omega(t) \equiv m$)

- Full vaccine coverage and no susceptibility,

$$\mathcal{E}_1 = (S_1, I_1, x_1) = (0, 0, 1)$$

- No vaccine coverage and full susceptibility,

$$\mathcal{E}_2 = (1, 0, 0)$$

- Partial vaccine coverage and partial susceptibility,

$$\mathcal{E}_3 = (1 - x_3, 0, x_3)$$

where $x_3 = \frac{1}{2}(1 + \frac{m}{\delta})$ and $\delta > m$.

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Model equilibria

Endemic equilibria

When perceived risk of vaccination is constant ($\omega(t) \equiv m$)

- No vaccine coverage

$$\mathcal{E}_4 = (\frac{1}{R_0}, \frac{\mu}{\mu+\gamma}(1-\frac{1}{R_0}), 0)$$

where $R_0 = \dfrac{\beta}{\mu+\gamma} > 1$

- Partial vaccine coverage

$$\mathcal{E}_5 = (\frac{1}{R_0}, I_5, x_5)$$

where

$$I_5 = \frac{\mu(m-\delta+\frac{2\delta}{R_0})}{\mu-2\delta(\mu+\gamma)} \quad \text{and} \quad x_5 = \frac{\mu(1-\frac{1}{R_0})-(\delta+m)(\mu+\gamma)}{\mu-2\delta(\mu+\gamma)}.$$

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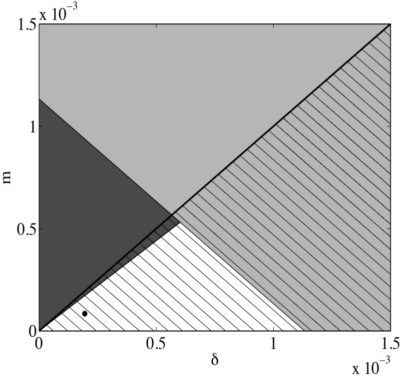
$$\mathcal{E}_5 = \left(\frac{1}{R_0}, I_5, x_5\right)$$

  where

$$I_5 = \frac{\mu\left(m-\delta+\frac{2\delta}{R_0}\right)}{\mu-2\delta(\mu+\gamma)} \quad \text{and} \quad x_5 = \frac{\mu\left(1-\frac{1}{R_0}\right)-(\delta+m)(\mu+\gamma)}{\mu-2\delta(\mu+\gamma)}.$$

Dynamical regimes

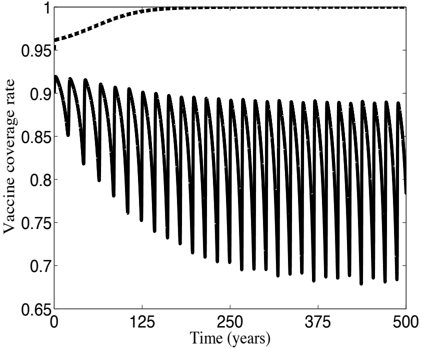
When perceived risk of vaccination is constant ($\omega(t) \equiv m$)

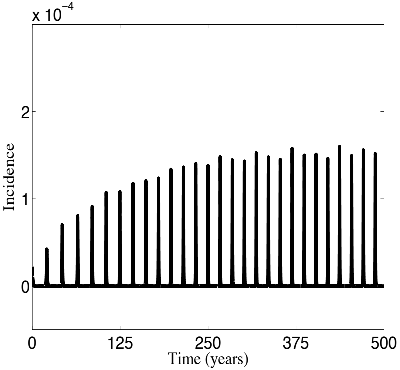


- $\mathcal{E}_1 = (0, 0, 1)$ the hatched region
- $\mathcal{E}_4 = (\frac{1}{R_0}, \frac{\mu}{\mu+\gamma}(1 - \frac{1}{R_0}), 0)$ the light grey region
- $\mathcal{E}_5 = (\frac{1}{R_0}, I_5, x_5)$ the dark grey region on the left

Dynamical regimes

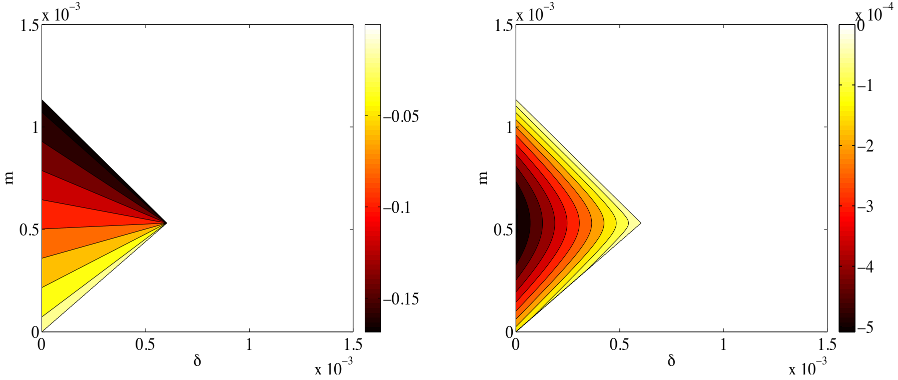
Simulations





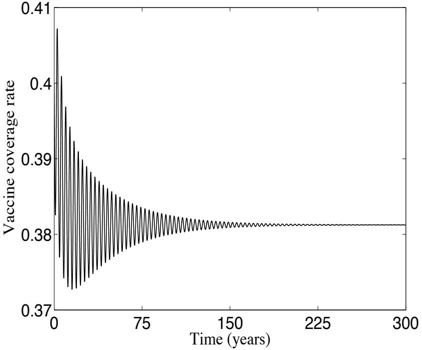
Dynamical regimes

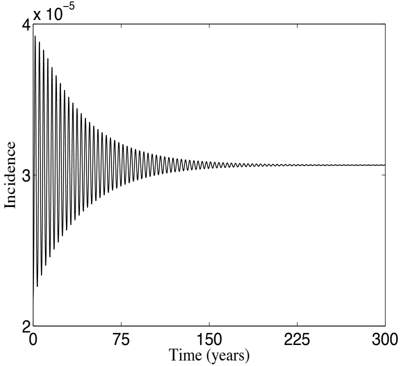
Simulations



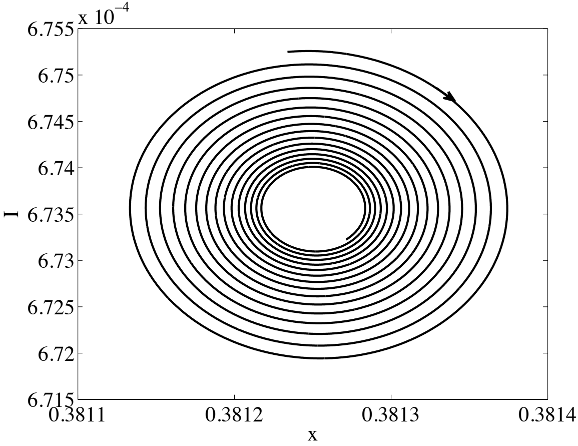
Dynamical regimes

Simulations





Dynamical regimes
Simulations



Dynamical regimes

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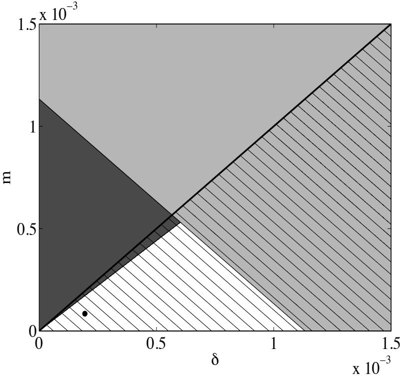

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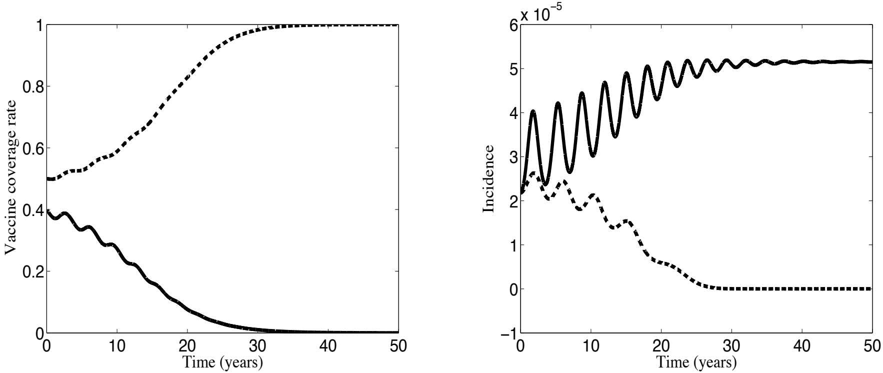
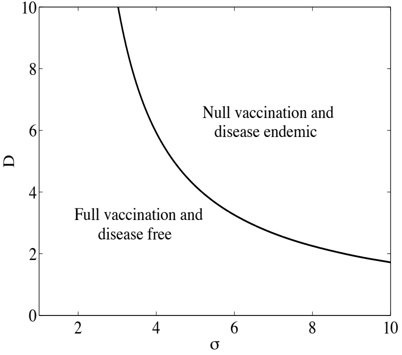
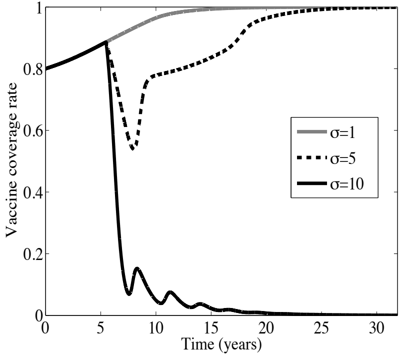


Dynamical regimes

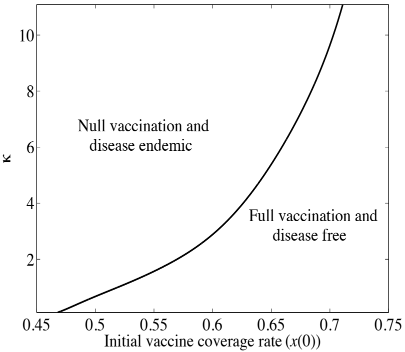
Simulations

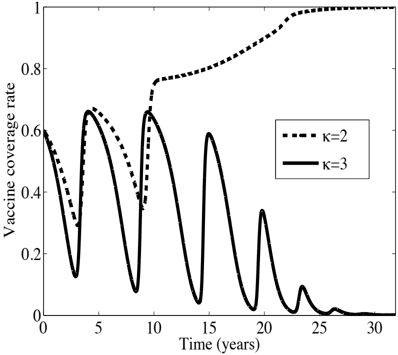




Dynamical regimes

Simulations





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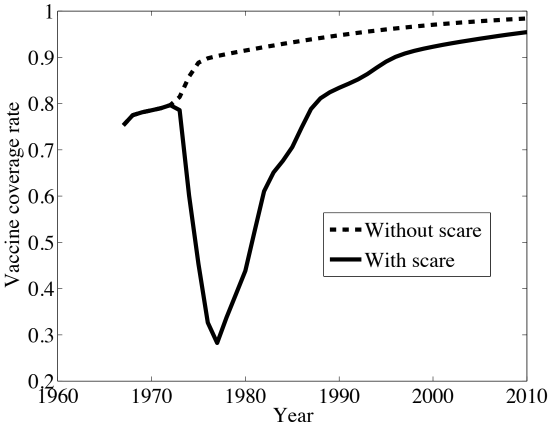
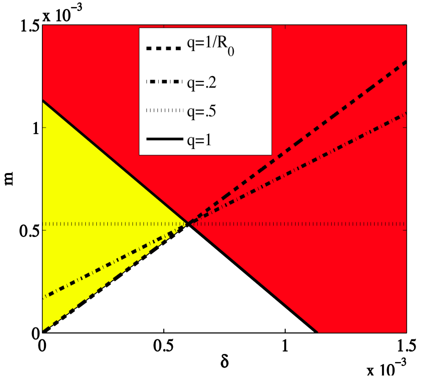


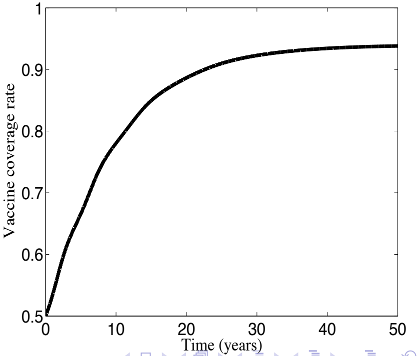
Dynamical regimes

Simulations

q is proportion of all-time non-vaccinators

$$\frac{dx}{dt} = \kappa\, x\,(1 - x - \ q\ )\,(-m + l + \delta\,(2\,x - 1))$$





Dynamical regimes

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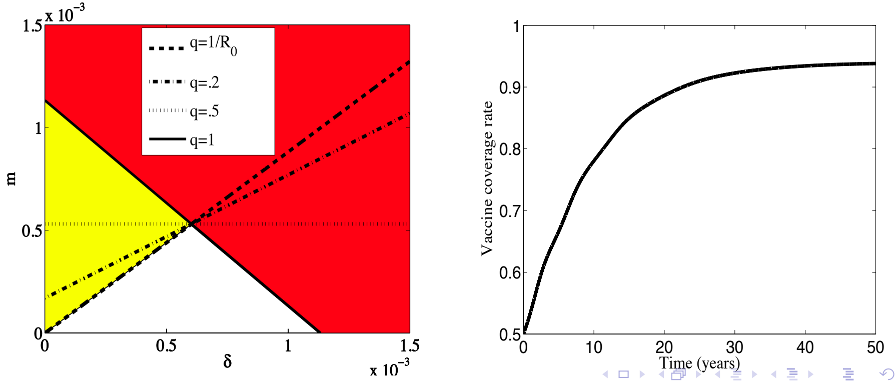

Outline

- Incorporating social norms into disease-behavioral models enables them to capture both vaccine refusal and vaccine acceptance behavioral regimes
- Our model shows how social norms can stabilise dynamics, reducing the amplitude and likelihood of oscillations in vaccine uptake
- Social norms can either boost vaccine coverage, or can drag coverage below levels that are optimal

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How Peer Pressure Explains Vaccination Rates

By Stephanie Pappas, Senior Writer | February 11, 2014 07:01pm ET

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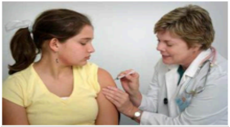

The nurse in this 2006 photograph was in the process of administering an intramuscular vaccination in the left shoulder muscle of a young girl. The nurse was pinching the overlying shoulder skin, in order to immobilize the injection site.

Credit: CDC View full size image

In a purely rational world, vaccination rates would vacillate constantly depending on how much people fear getting sick.

That's what attempts to model vaccination rates mathematically have found. But now, scientists have added in the missing puzzle piece that explains why vaccination rates stay high in the real world — or, in some cases, low. The reason, it turns out, is peer pressure.

Public health officials frequently worry about low levels of childhood vaccination, often driven by debunked concerns that vaccines are linked with autism. But in many nations without mandatory vaccination rules, rates of childhood vaccination remain surprisingly high, said Tamer Oraby, a mathematician at the University of Guelph in Ontario, Canada. [5 Dangerous Vaccination Myths]

Thank you