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Predicting changes in reported notifiable disease rates for New Zealand using a SIR modelling approach

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The New Zealand health system has defined as 'notifiable' over 50 diseases. Of these campylobacteriosis is the most commonly reported comprising 41% of all notifications in 2011 (presently about 150 illness cases per 100,000 population per annum). Furthermore, the incidence of this mild illness, which is potentially waterborne, is under-reported by at least an order-of-magnitude. Increased downstream pathogen loads and/or disease incidence have been found to be associated with increased rainfall, particularly in agricultural landscapes. Therefore, given the predominance of agricultural land uses in New Zealand, transmission and exposure to its agent (thermotolerant Campylobacter bacteria) may be affected by changing rainfall and temperature patterns associated with climate change. Reporting rates for other potentially water-borne zoonoses are also noticeable (for example, the reported rate for cryptosporidiosis for 2011 was 14 per 100,000 population). The distribution of Cryptosporidium oocysts in the environment may be influenced by climate change because it has often been implicated in drinking-water contamination, and heavy rainfall events have been found to be associated with increased pathogen loads in rivers and disease incidence. Given this background, which may also be applicable to other countries with agriculturally-dominated landscapes, a New Zealand study was initiated to develop a decision-support system for the projected effects of climate change on a selected suite of environmentally-transmitted pathogens, including Campylobacter and Cryptosporodium oocysts. Herein we report on the manner in which a linear SIR (Susceptible-Ill-Recovered) model previously developed for campylobacteriosis can be extended to cryptosporidiosis, applied to changes in pathogen contact rate and hence reported illness, and coupled to climate change projections associated with different greenhouse gas emission scenarios. The resulting SIR model outputs provided projected changes in reported disease incidence as a function of temperature and rainfall. These models account for age-dependency (children versus adults), which is especially important because children can report substantially higher rates of zoonoses. The model is linear because the zoonotic pathogen 'reservoir' is overwhelmingly among animals, and so the usual interaction in which human-pathogen interactions affect the degree of environmental contamination does not apply in the short term (on the order of one year). Accordingly, the interaction can be approximated by a constant contact rate over a given year, even though the contact rates may vary between decades because of climate change and variability. This linearity property enables the derivation of analytical solutions to the model's governing equations, thereby providing for a more elegant examination of the model's properties and for making projections under climate change. The models have been calibrated to reported rates of these diseases. Simple exponential functions have been used to vary the pathogen contact rates for the reference years 2015, 2040 and 2090 under three climate change scenarios of low, medium and high emissions of greenhouse gases (B1, A1B, and A2). These formulations have been guided by the results of statistical models calibrated to historical disease reporting rates. The models have been used to calculate the ratio of reported illness rates to present rates projected for future years across New Zealand at the ~5 km scale. Detailed results will be presented for the reference year 2040.

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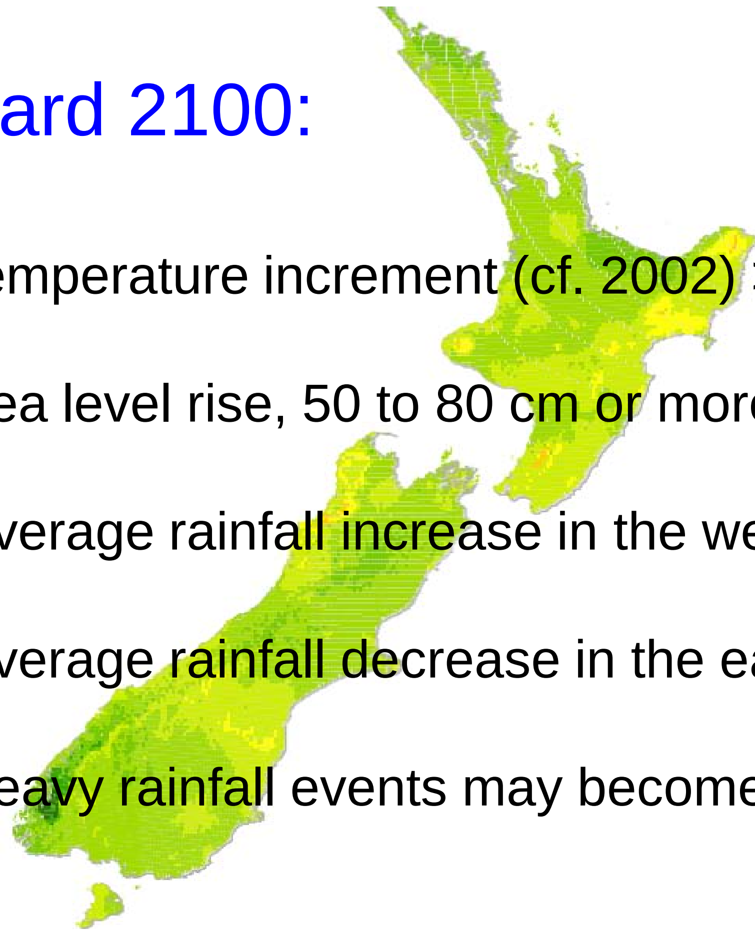
Projected Climate Change Effects*

Toward 2100:



temperature increment (cf. 2002) > 4 ^{o}C?

sea level rise, 50 to 80 cm or more

←Australia

average rainfall increase in the west and south

average rainfall decrease in the east and north

heavy rainfall events may become more severe

* Reisinger *et al*., 2010 Global and local climate change scenarios to support adaptation in New Zealand. *In*: Climate change adaptation in New Zealand: Future scenarios and some sectoral perspectives. Nottage *et al*. (eds). New Zealand Climate Change Centre, Wellington, pp. 26-43.

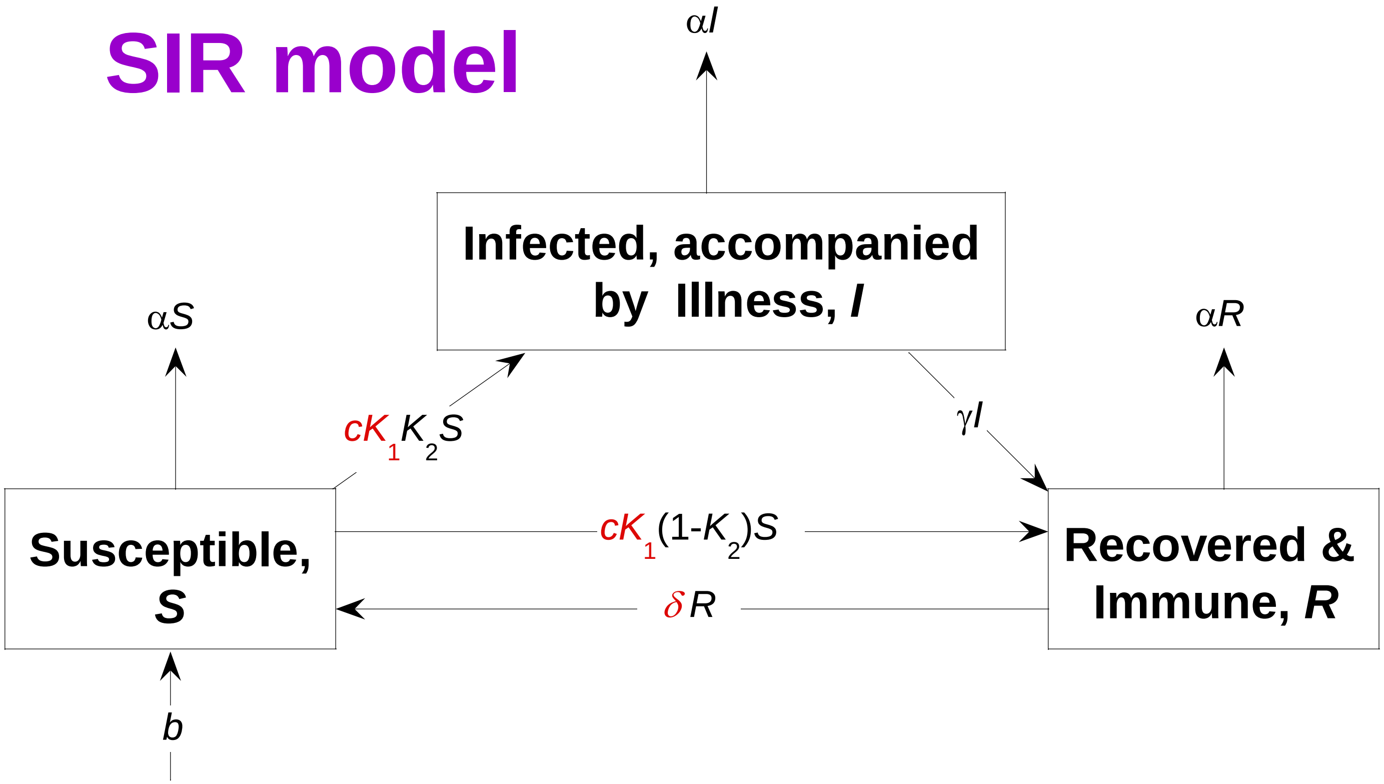
Context of our study

- New Zealand landscape dominated by agriculture
- >50 diseases ”notifiable”
- Dominated by zoonoses
  - Campylobacteriosis (41%, ~200 reported cases per 100,000 p.a.)
  - Also cryptosporidiosis (3%, ~15 reported cases per 100,000 p.a.)
  - Under-reported, by at least an order-of-magnitude
  - Microbiological agents (pathogens) can be transmitted via water
- Increased rainfall → increased pathogen load and disease
- Build a DSS
  - For six pathogens, proof-of-concept

Approach

- Use a (published) age-dependent, non-epidemic SIR model
  - SIR = Susceptible – Infected/Ill – Recovered
  - Calibrated to National Disease data (EPISURV)
- Make calculations for *relative* changes in *reported* illness
  - Using statistical models of health and environment

SIR model



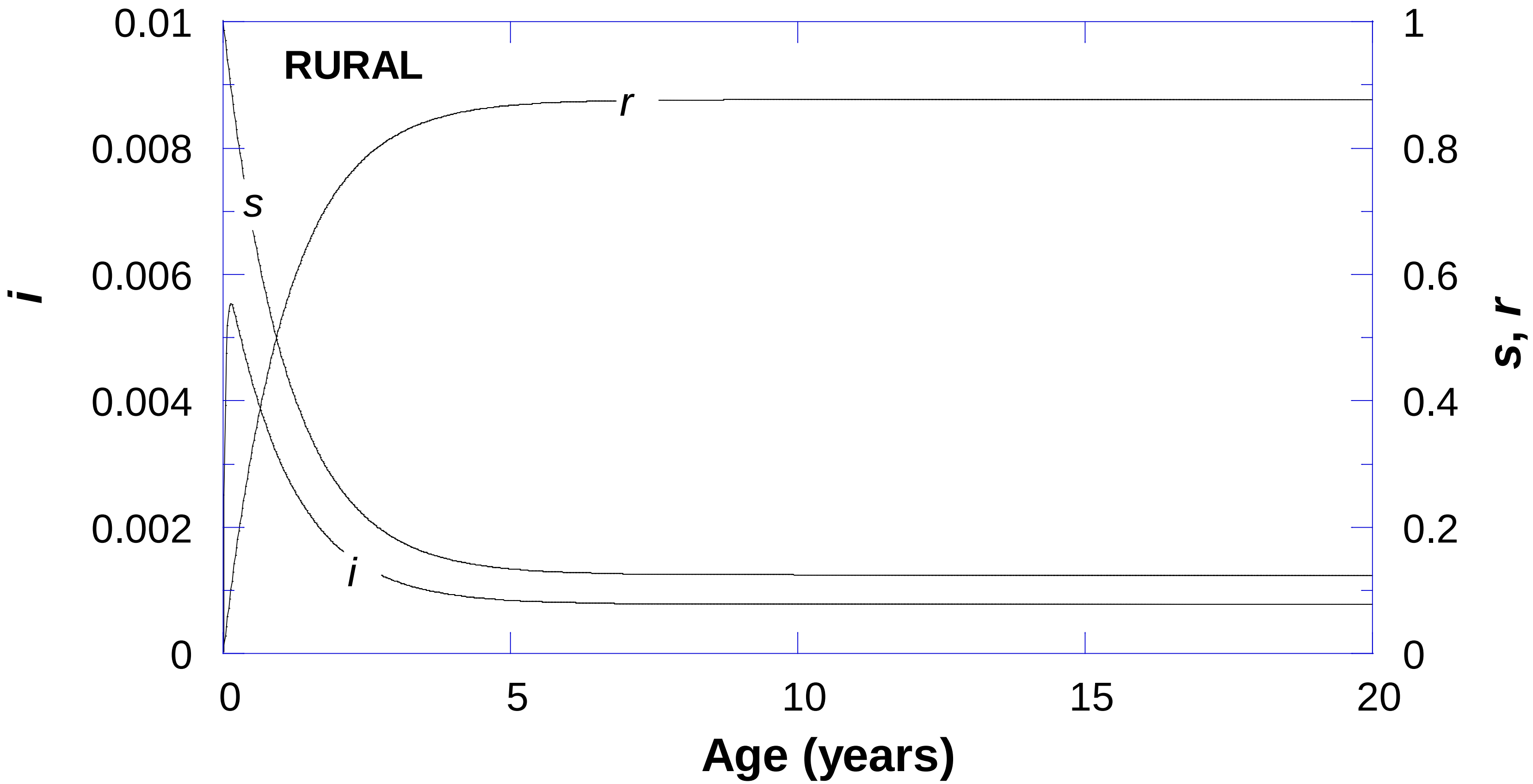
Birth rate (*b*)
Death rate coefficient (α)
Pathogen contact rate (*c*)
Probability of infection given contact with pathogen (K_1)
Probability of illness given infection (K_2)
Reciprocal of the shedding period (γ)
Immunity loss rate coefficient (δ)

Solutions

- Closed-form analytical solutions*
  - Direct – no iterations required (☺)
  - Calibrated to EPISURV, for *reported* rates (☺)
- Reveals adult (Methuselah) rate
- "TPA" (Turning Point Analysis) reveals maximum (childrens') rate (☺)
  - Larger than the adult rate
  - Confirmed by EPISURV data

*McBride, G.B.; French, N.P. (2006). Accounting for age-dependent susceptibility and occupation-dependent immune status: a new linear analytical model. *WSEAS Transactions on Mathematics 11(5)*: 1241–1246

SIR Campy Model example results: Note child illness rate peak



SIR results: c = 8, α = 0.0125 p.a., K_1 =0.1, K_2 =0.2, g = 0.1 p.a., γ = 26 p.a.

Basic Assumption

Consider the product cK_1 = frequency of contact with a pathogen that leads to infection. Assume that only cK_1 changes between the years.

Adults

Change = ratio of reported Methuselah rates between the years

Children

Change = ratio of maximum reported rates from TPA

Accounting for Climate Change

Key assumption

$$\left(cK_1\right)_f = \left(cK_1\right)_r \mathrm{e}^{\left(\beta_R \Delta R + \beta_T \Delta T\right)}$$

"$_f$" = future;

"$_r$" = reference year;

ΔR & ΔT = projected changes in Rainfall & Temperature;

β_R & β_T = associated rate coefficients.

Campylobacteriosis SIR parameters

Urban adults

- Pathogen contact rate $c = 2$ (p.a.)
- Natural death rate $\alpha = 0.0125$ (p.a.)
- Prob(infect. | pathogen contact) $K_1 = 0.1$
- Prob(illness | infection) $K_2 = 0.2$
- Reciprocal of shedding period $\gamma = 26$ (p.a.)
- Immunity loss rate $\delta = 0.35$ (p.a.)

Campylobacteriosis

Define ρ = relative change in reported rates. For given parameters

$$\rho_{\text{adult}} \approx \frac{1-\mathrm{e}^{-\xi}}{\varepsilon_r + \mathrm{e}^{-\xi}} \text{ where } \xi = \left(\beta_R \Delta R + \beta_T \Delta T\right), \text{ and } \varepsilon_r = \frac{c_r K_1}{\delta}$$

- ρ_{child} more complex

- ρ calculated on a 5x5 km grid of predicted rainfall and temperature for 2015, 2040, 2090 and three CC scenarios (B1, A1B, A2)

Rainfall & temperature coefficients

Statistical modelling & freshwater study (Till *et al*. 2008)* $\Rightarrow$ campylobacteriosis increases with rainfall and temperature.

- Rainfall

  Assume cK_1 increases by 50% under maximum <u>increase</u> of projected rainfall (783 mm/y, winter 2090), so $\beta_R \approx 0.0005$ /mm (reduction to 86% under maximum rainfall <u>decrease</u>, –295 mm/y, autumn 2090).

- Temperature

  Assume cK_1 increases by 25% under maximum <u>increase</u> of projected temperature (3.686 ^{o}C, summer 2090), so $\beta_T \approx 0.06$ / ^{o}C (reduction to 94% under maximum temperature <u>decrease</u>, –0.99 ^{o}C, autumn 2040).

*Till, D. *et al*. (2008). Large-scale freshwater microbiological study: Rationale, results and risks. *J. Water & Health 6(4)*: 443–460.

Campylobacteriosis—other cases

- Gender models
  - Males report higher rates cf. females. Accounted for by setting $K_{1,\ \text{males}} = 0.015$, and $K_{1,\ \text{females}} = 0.0075$

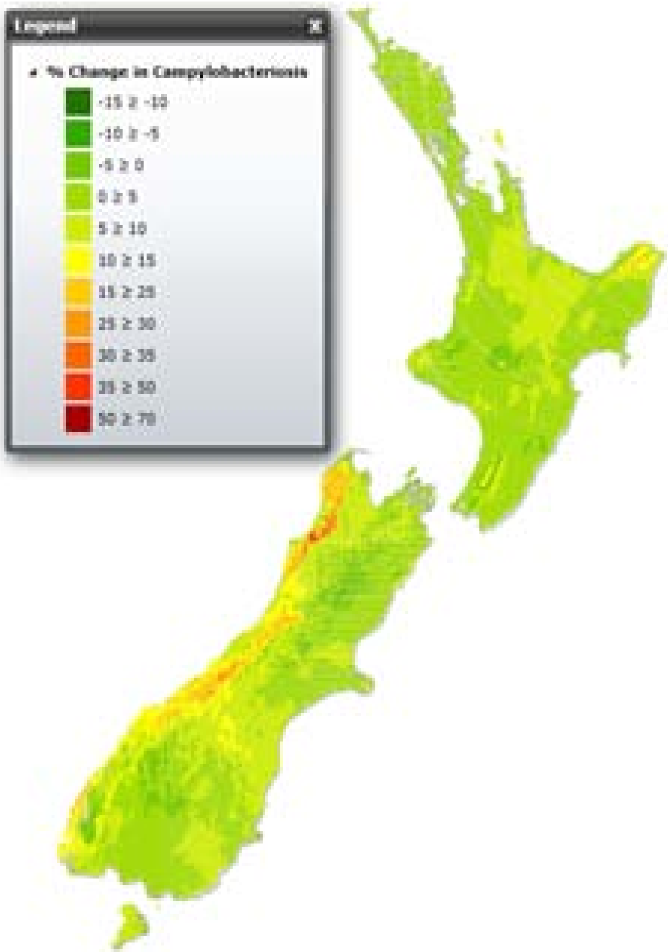
- Children
  - First calculate the age at which the (child) maximum reported rate occurs, then calculate the illness proportions on the 5 x 5 km grid. All calculations direct & fast.

Cryptosporidiosis SIR parameters

Pathogen contact rate	c	= 1 (p.a.)
Natural death rate	α	= 0.0125 (p.a.)
Prob(infect. | pathogen contact)	K_1	= 0.2
Prob(illness | infection)	K_2	= 0.2
Reciprocal of shedding period	γ	= 26 (p.a.)
Immunity loss rate	δ	= 0.025 (p.a.)
Rainfall coefficient	β_R	= 0.0005 (/ mm)
Temperature coefficient	β_T	= 0.11 (/ ^{o}C)

Campylobacteriosis: Children vs. all ages, Spring 2040, A2 scenario

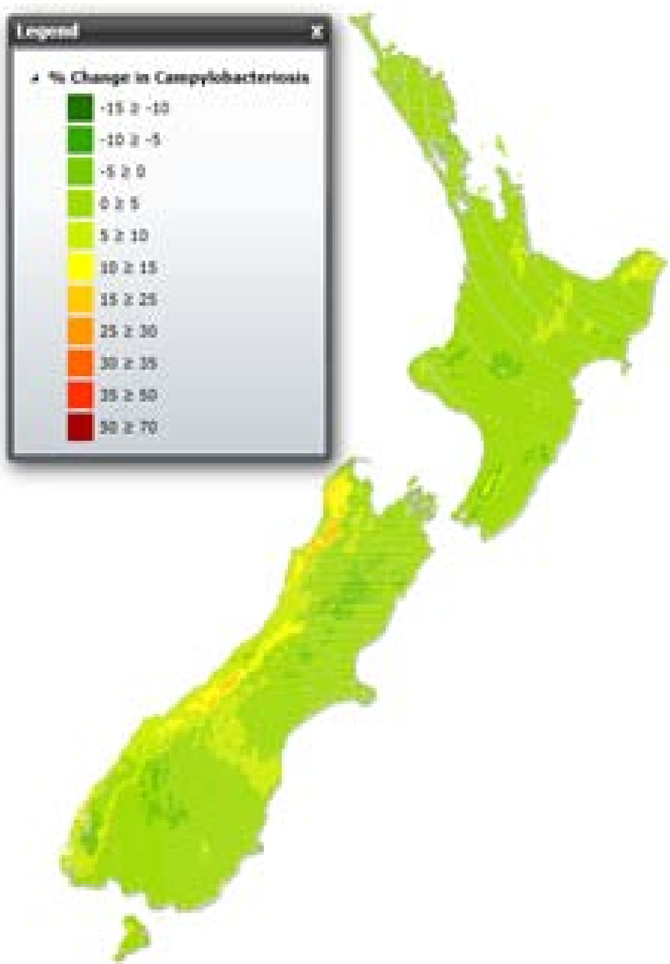
Children (0 – 4 y)



All ages

Campylobacteriosis: Female vs. male, Spring 2040, A2 scenario

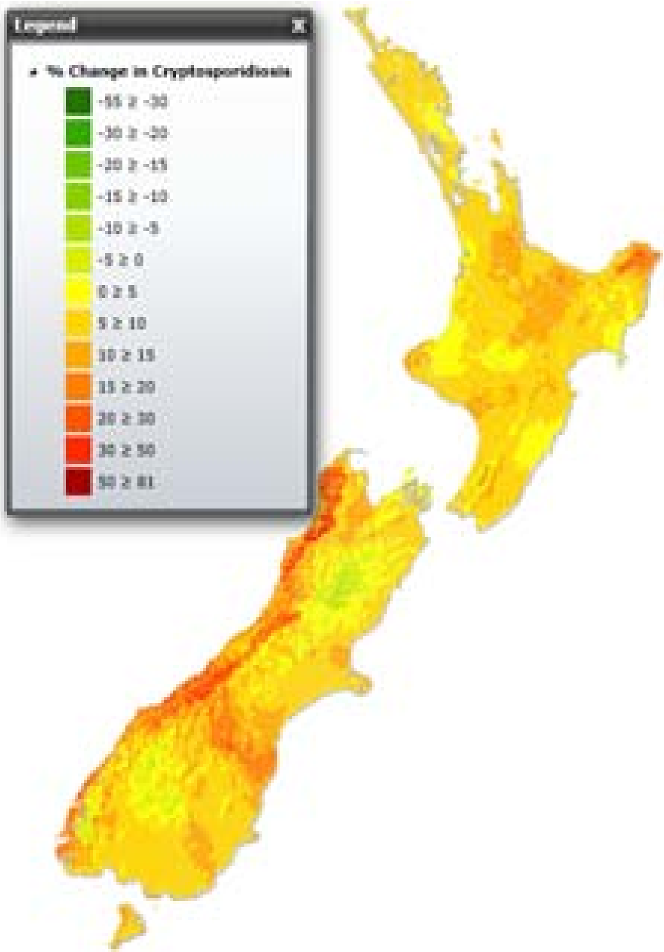
Female



Male

Cryptosporidiosis: Children versus all, Spring 2040, A2 scenario

Children (0 – 4 y)



All ages

General patterns (2040, A2)

General

- Reductions possible on east coasts
- Maximum increase in summer, maximum decrease in autumn
- More extreme in 2090

Campyobacteriosis

- Spatial average increase (~4%)
- Changes for children (6%) > changes for adults
- Changes for females > males (25% higher)

Cryptosporidiosis

- Spatial average increase (<1%)
- Changes for children (9%) > adults

Conclusions

- Results plausible; accepted by project oversight
- Biggest changes on west coasts, but population density higher on east coasts $\Rightarrow$ overall impact lessened
- For children: Changes in cryptosporidiosis > changes in campylobacteriosis
- Ignores any effect of interventions (e.g., more control and so reduction of load from poultry industry) or changes to the country’s socio-economic status
- Results to be available on an accessible website