Draft final report
Measles risk assessment, modelling and benefit–cost analysis

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1 Abstract

New Zealand has been working towards elimination of endemic (domestic) measles virus transmission, but has suffered from small, yet significant outbreaks of measles after measles introductions from abroad. In this draft final report we review the draft *Progress Towards Measles Elimination in New Zealand - Final* report from the New Zealand Ministry of Health to the World Health Organization (WHO) Western Pacific Region. We identified additional analyses that may help understand risk of infection in New Zealand, and present the results of statistical analyses of risk factors for measles cases in New Zealand during outbreaks since 2007. We provide cost analyses for the measles outbreaks in New Zealand, and include modelling of measles outbreaks, including pre- and post-vaccination scenarios, based on the numbers of naive people at the District Health Board (DHB) and national level. We provide benefit–cost analyses using the results from those model simulations, along with a number of alternative vaccination strategies to achieve different vaccination coverage levels. Our key findings were:

- The *Progress Towards Measles Elimination in New Zealand - Final* report was of high quality and contained substantial information and useful analyses.

- Age is the best predictor of risk of measles infection in multivariate regression analyses, though some groups, such as people of Pacific ethnicity, the less socially deprived, and European and Maori school age children have been more likely to be measles cases in outbreaks since 2007.
- New Zealand is at risk of frequent measles importation due to travel and endemic measles elsewhere in the globe.
- Peak overall travel rates, and thus presumably risk from measles importation, is in December. However, New Zealander and immigrant or non–New Zealander travelling is otherwise out of phase, with peak travel for New Zealanders during the winter, and non–New Zealanders summer.
- Analyses of outbreak data suggest that measles basic reproductive number (R_v, the number of secondary infections) values often include 1 and this year, 2014, as analysed from data from April, is well above one. This analysis suggests improved vaccination is a requisite to prevent measles becoming endemic again.
- Estimates of the proportion of the currently naive New Zealand population requiring additional vaccination to ensure measles does not persist is approximately 28%, leading to an additional 131,500 vaccinations.
- The cost of the current 2013–2014 measles outbreak is estimated to be at least $809,000.
- The benefit–cost ratio analyses suggest additional vaccination is extremely beneficial financially.

2 Background

As a member of the World Health Organization (WHO) Western Pacific Region, New Zealand is committed to work towards measles elimination, defined as the interruption of endemic (domestic) measles virus transmission, as achieved in the Americas in 2002. The Western Pacific Region is expected to be the second WHO region to achieve measles elimination and it was announced that in March 2014 that Australia, Macao, Mongolia and the Republic of Korea have achieved measles elimination.

The last widespread measles outbreaks in New Zealand occurred in 1991 and in 1997. Since then, smaller but significant outbreaks have occurred in 2009 (mainly in Canterbury) and in 2011–2012 (mainly in the Auckland region) and another significant outbreak is currently ongoing in the Auckland and Waikato regions. The outbreak in 2011–2012 lasted for more than 12 months and the current 2013–2014 outbreak started at the end of December 2013 and is ongoing (as of 3 July 2014). In 2013, prior to the 2013–2014 outbreak, New Zealand was advised by the Western Pacific Regional Verification Commission for Measles

Elimination (RVC) that it can request verification of non-endemic status three years after the last case of the 2011–12 outbreak in June 2012.

Previous measles analyses, including two in New Zealand by Prof. Roberts, estimated the interruption of measles virus transmission can be achieved by herd immunity when approximately 95 percent of the population is homogeneously immune to measles [29, 28]. Thus, while New Zealand immunisation activities have led to measles outbreaks becoming less frequent, with decreasing numbers of cases, outbreaks still occur (as described above). Current overall population immunity estimates suggest that approximately 85 to 90 percent of the population is immune to measles, thus the reasons for the ongoing outbreaks are likely due to overall population immunity being less than 95 percent and there being pockets of susceptible, non-immune population remaining. Since 2009, all the outbreaks in New Zealand were linked to infections acquired (imported) from overseas, though previous work suggests these outbreaks still largely affect school-aged children and children under two years of age. Under two year olds are thought be be consistently among the most affected age groups because the first of two doses of measles, mumps and rubella vaccine (MMR) is not due until fifteen months.

3 Risk analysis review

A measles risk assessment has been undertaken by the Ministry of Health to better assess current and future population immunity and high risk groups. Given the current measles outbreak, measles control is a priority for the Ministry and resources are available to control this outbreak and decrease the risk of future outbreaks.

- In this section we review the confidential report to the Western Pacific Regional Verification Commission for Measles Elimination risk assessment provided by the Ministry, titled *Progress Towards Measles Elimination in New Zealand - Final*.

Overall, the review was very thorough. The report included substantial background information on measles immunisation in New Zealand (*Section 1.3*), the epidemiology of measles in New Zealand (*Section 2*), the quality of epidemiological surveillance and laboratory testing for measles (*Section 3*), and the levels of population immunity against the virus (*Section 4*). Additional details are included for many aspects of measles epidemiology and control, not least regarding the recent MMR coverage rates by birth cohort in New Zealand (*Section 4.2*) and the sustainability of the national immunisation programme (*Section 5*).

Within the report there are many tables and figures which give considerable detail on the measles situation in New Zealand. Overall these were of high quality, reporting both absolute measles case numbers and rates per 100,000 population in New Zealand.

Specific epidemiological details were provided for the 2011–2012 outbreak including *Figure 4*, the number and classification of measles notifications in

New Zealand by month and year (2011 and 2012), with additional breakdown by age group in both years (*Figure 5*) and per 100,000 population (*Figures 6–8*). Similar presentation of the case data are provided for ethnicity (*Figures 9–10*) and New Zealand Index of Deprivation (NZDep) (*Figures 11–13*). Three figures, *Figures 12, 13,* and *28*, show that there is spatial clustering of cases.

The report concludes that New Zealand's surveillance system has been performing well and that the Ministry is confident that measles has not been circulating since June 2012 and has not become endemic in NZ. We agree with the statement that measles did not become endemic and provide some preliminary analyses on the outbreaks since endemic measles elimination (see section 5) that give information regarding the likelihood of measles persisting within the population and becoming endemic, including important analysis of the current outbreak.

We agree with the report conclusions that testing for measles is performed appropriately within the required timeframe. Clearly improving inter-laboratory communication and collaboration and timeliness of the testing and reporting is necessary for rapid responses to measles introductions following measles control. Vaccination coverage presented in the report and to ourselves confirms that immunisation levels are approaching 94% for MMR dose one (birth cohorts 2009 and 2010) and 89% for MMR dose two (birth cohorts 2006 and 2007). However, only Asian and Pacific ethnicities have consistently had MMR dose one coverage approaching or exceeding 95% for cohorts from 2007 onwards, and thus we agree with the report's conclusions that timeliness and coverage of vaccination need improving. This is particularly in light of our preliminary modelling and risk analyses results (section 4 and section 5).

4 Additional risk analyses

In this section we provide work that we believe will help inform the Ministry of Health regarding the understanding of risk from measles. These analyses are intended to build on the analyses already included in the *Progress Towards Measles Elimination in New Zealand - Final* report reviewed above.

We include multivariate modelling to account for confounding within the univariate analyses for measles cases in New Zealand, and descriptive analyses of risk of infection due to previous vaccination history, current rates of immunity within the population. In light of the apparent increasing trend in measles incidence in the last few years (Figure 1), we reviewed the information on measles importation and the origins of the introductions of measles into New Zealand. To help understand the risk of measles importation, with a particular goal of enabling the Ministry to better inform travellers and understand high risk periods, we sought to quantitatively evaluate the risk of measles importation from travel.

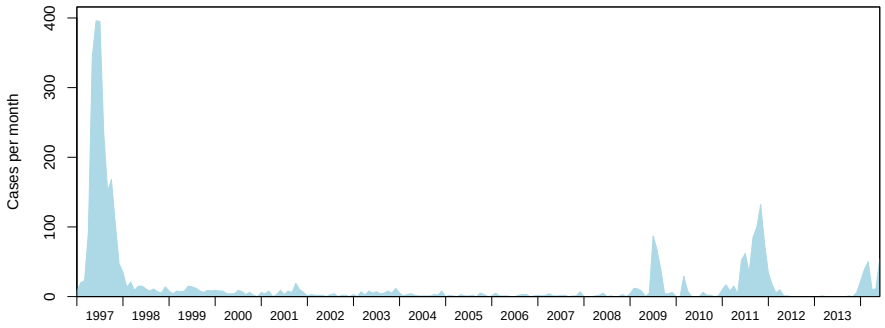

Figure 1: Measles incidence from 1997 to 2014

4.1 Risk of measles infection in New Zealand analyses methods

We received the raw EpiSurv measles case data from The Institute of Environmental Science and Research Ltd (ESR) on 27 June 2014. Initial analyses of those ESR data (not shown) suggested that denominator data were required to perform multivariate analyses to avoid confounding results due to a lack of independence among risk factors. Specifically we required Age×Prioritised Ethnicity× NZDep data for New Zealand to test whether interactions among case covariates provide additional information on risk over the univariate analyses performed in the *Progress Towards Measles Elimination in New Zealand - Final* report. These Age × Prioritised Ethnicity × NZDep data were provided to us on 3 July 2014 by the University of Otago. We used these denominator data to determine if there were interactions among specific age categories, Prioritized Ethnicities, and NZDep that might exist among cases allowing better understanding of risk of measles infection.

The University of Otago denominator data provided were not to the same detail as the ESR case data. Notably, the denominator age data were categorised into several classes: 0–5, 6–17, 18–24, 25–64, and 65+ year categories. The ethnicity denominator data were not Prioritized Ethnicity at the Level 1 Ethnic Group Codes, but at the Level 2 Ethnic Group Codes, though with some alternative codes provided that did not match the Level 2 Ethnic codes. After discussions with the University of Otago we have provided results based on the best available data, though for smaller ethnic group categories, some results may be unreliable and these are discussed below.

With the 10 NZDep classes, Prioritized Ethnicities, and the age classes above, the numerous combinations of variables led us to have 250 categories. Because for measles cases the very young appear to be disproportionately af-

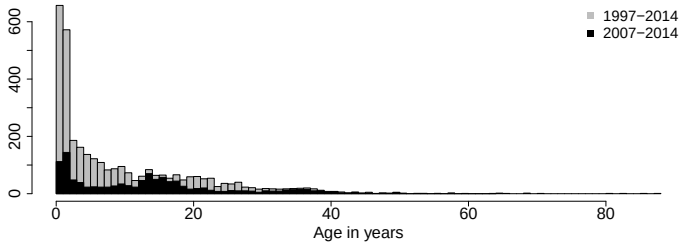

Figure 2: Age of measles cases in years in New Zealand for two periods, 1997–2014 and 2007–2014

fected (Figure 2), we split the 0–5 age category into two classes, 0–2 and 3–5 years old for each of the University of Otago denominator data, assuming equal numbers of young were born into each age group over the last five years (which is supported by data from NZ statistics [33]).

This large number of categories, some with small population sizes, lead to both overdispersion and zeroinflation, as there were many categories with zero cases in, particularly in the adult age classes. Furthermore, initial preliminary analyses, including multi– and univariate analyses (not shown) suggested little effect of individual NZDep classifications and several higher order interactions, and therefore we reduced the number of NZDep categories from ten to two: NZDep 1–5 and NZDep 6–10. We also incorporated the 65+ age classes into the 25–64 age category, to make a 25+ age category. By doing so, we reduce the zeroinflation present in the data.

The Prioritized Ethnicities for cases are: European; Maori; Pacific Peoples; Asian; Middle Eastern/Latin American/African (MLA); Other Ethnicity; Residual Categories. For the analyses in this report only the first five are used, as these categories cover the overwhelming number of cases, with only 1.9% (22/1137) of cases having no Prioritized Ethnicity (see *None*, Table 1).

The numbers of cases per category and population sizes for the complete data set from 2007-2014 can be seen in Table 2. Subsequent regression analyses (not shown) also suggested that the Middle Eastern/Latin American/African category was over– or underrepresented in per capita rates given the very small sample sizes for this classification (Figure 3, Table 2), leading to very large standard error in regression analyses. However, there are numerous issues with the data for Middle Eastern, Latin American and African ethnicities category, and along with small population sizes (Table 2), and there several issues with estimating the denominator data for this group (University of Otago, personal communication). Thus, we removed this grouping for our subsequent analyses and are left with Asian, European, Maori and Pacific as Prioritized Ethnicities. This left us with 1102/1115 (99%) of the measles cases with Prioritized Ethnicity recorded from 2007, and 1102/1137 (97%) of all measles cases recorded since

NZDep	Age	Ethnicity	Cases
1-5	0-2	Asian	11
6-10	0-2	Asian	8
1-5	3-5	Asian	1
1-5	6-17	Asian	11
6-10	6-17	Asian	5
1-5	18-24	Asian	3
6-10	18-24	Asian	5
1-5	25+	Asian	10
6-10	25+	Asian	13
1-5	0-2	European	83
6-10	0-2	European	64
1-5	3-5	European	42
6-10	3-5	European	17
1-5	6-17	European	219
6-10	6-17	European	80
1-5	18-24	European	34
6-10	18-24	European	36
1-5	25+	European	78
6-10	25+	European	51
1-5	0-2	Maori	18
6-10	0-2	Maori	48
1-5	3-5	Maori	7
6-10	3-5	Maori	11
1-5	6-17	Maori	19
6-10	6-17	Maori	92
1-5	18-24	Maori	5
6-10	18-24	Maori	8
1-5	25+	Maori	2
6-10	25+	Maori	6
6-10	0-2	MLA	3
6-10	3-5	MLA	1
6-10	6-17	MLA	1
6-10	18-24	MLA	2
6-10	25+	MLA	6
1-5	0-2	Pacific	5
6-10	0-2	Pacific	58
6-10	3-5	Pacific	3
1-5	6-17	Pacific	5
6-10	6-17	Pacific	22
1-5	18-24	Pacific	1
6-10	18-24	Pacific	8
1-5	25+	Pacific	2
6-10	25+	Pacific	11
1-5	0-2	None	3
1-5	3-5	None	1
1-5	6-17	None	3
6-10	6-17	None	4
1-5	18-24	None	2
6-10	18-24	None	1
1-5	25+	None	5
6-10	25+	None	3

Table 1: Absolute number of measles cases in specific age, ethnicity and socio-economic deprivation categories from 2007-2014

2007 (Table 2).

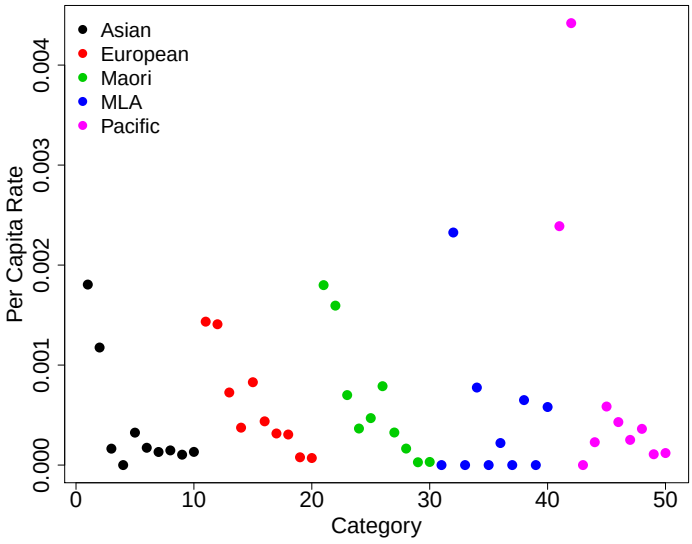

Figure 3: Per capita rates of measles infections broken down by ethnicity, see Table 2 for details

For all our statistical analyses (including those above not shown) we used a Poisson error structure, but in all cases there was a need to account for overdispersion and thus we used and present the results of a quasipoission regression model. We also account for differences in population sizes by using an offset term, the log(population size). We used a model simplification approach, by beginning our analyses with all terms and all interactions, and then simplifying the models through removal of non-significant higher order interaction terms. Thus, the final model that remained with all significant interaction terms had the following linear predictor:

$$log(y) = \alpha + \beta_a(x_a) + \beta_e(x_e) + \beta_n(x_n) + \beta_{ae}(x_a * x_e) + log(population) + \epsilon \quad (1)$$

Where α is the intercept, y cases, $_a$ age, $_e$ Prioritized Ethnicity, $_n$ NZDep, and ϵ the error term.

4.2 Measles importation risk

For our measles importation risk analyses, we use arrivals data from New Zealand immigration and New Zealander travel data by country and year (www.immigration.govt.nz) to measure human movement to and from New Zealand. We collated country

Table 2: Numbers of measles cases, population sizes and per capita rates of measles in specific age, ethnicity and socio-economic deprivation categories from 2007-2014

NZDep	Age	Ethnicity	Population	Cases 1	Per capita
1-5	0-2	Asian	6094	11	0.0018
6-10	0-2	Asian	6806	8	0.0012
1-5	3-5	Asian	6094	1	0.0002
6-10	3-5	Asian	6806	0	0.0000
1-5	6-17	Asian	33918	11	0.0003
6-10	6-17	Asian	28905	5	0.0002
1-5	18-24	Asian	22917	3	0.0001
6-10	18-24	Asian	34107	5	0.0001
1-5	25+	Asian	96357	10	0.0001
6-10	25+	Asian	98715	13	0.0001
1-5	0-2	European	57872	83	0.0014
6-10	0-2	European	45445	64	0.0014
1-5	3-5	European	57872	42	0.0007
6-10	3-5	European	45445	17	0.0004
1-5	6-17	European	264330	219	0.0008
6-10	6-17	European	182937	80	0.0004
1-5	18-24	European	107649	34	0.0003
6-10	18-24	European	117840	36	0.0003
1-5	25+	European	1001916	78	0.0001
6-10	25+	European	724317	51	0.0001
1-5	0-2	Maori	10003	18	0.0018
6-10	0-2	Maori	30104	48	0.0016
1-5	3-5	Maori	10003	7	0.0007
6-10	3-5	Maori	30104	11	0.0004
1-5	6-17	Maori	40461	19	0.0005
6-10	6-17	Maori	116640	92	0.0008
1-5	18-24	Maori	15360	5	0.0003
6-10	18-24	Maori	48495	8	0.0002
1-5	25+	Maori	71217	2	0.0000
6-10	25+	Maori	192729	6	0.0000
1-5	0-2	MLA	728	0	0.0000
6-10	0-2	MLA	1290	3	0.0023
1-5	3-5	MLA	728	0	0.0000
6-10	3-5	MLA	1290	1	0.0008
1-5	6-17	MLA	2991	0	0.0000
6-10	6-17	MLA	4539	1	0.0002
1-5	18-24	MLA	1710	0	0.0000
6-10	18-24	MLA	3078	2	0.0006
1-5	25+	MLA	8028	0	0.0000
6-10	25+	MLA	10335	6	0.0006
1-5	0-2	Pacific	2093	5	0.0024
6-10	0-2	Pacific	13124	58	0.0044
1-5	3-5	Pacific	2093	0	0.0000
6-10	3-5	Pacific	13124	3	0.0002
1-5	6-17	Pacific	8541	5	0.0006
6-10	6-17	Pacific	51183	22	0.0004
1-5	18-24	Pacific	3972	1	0.0003
6-10	18-24	Pacific	22098	8	0.0004
1-5	25+	Pacific	18492	2	0.0001
6-10	25+	Pacific	91533	11	0.0001

population size, measles incidence and measles vaccination cover from the WHO (www.who.int/research/en/). Note the immigration figures use all immigration of foreign nationals, coming for whatever purpose and includes non-New Zealanders resident in New Zealand, but not yet holders of New Zealand passports. We used the WHO data to determine per capita measles cases for each year and used these data and the number of immigrants to New Zealand to begin to understand where measles was likely to be imported from. We used simple per capita rates for measles and the number of travellers to each country to score and map the risk of mealses importation. We use the data from 2012 because this year had the most complete WHO measles data and yet was most recent, thus accounts for improved measles vaccination coverage following the United Nations Millenium Development Goals' improvements in measles vaccination coverage.

4.3 Additional risk analyses results

Preliminary analyses of 2012 data, the most complete and current year of data, suggest immigration (whether for work, pleasure, etc.) is dominated by Australia, United Kingdom, China, and the United States, as shown in Table 5. However, vaccination coverage is lowest and measles incidence highest in less developed nations (Table 3 and Table 4). Though the precise interactions between these different risk factors are unknown, the most simple, a product of measles incidence in 2012 and immigration numbers in 2012, suggest that though immigration is lower from some Asian countries, travel from (and thus we presume to) some Asian countries also poses a high risk of measles importation to New Zealand. These data are shown in Table 10. The data for all the variables for each nation state and territories for 2012 are plotted in Figure 8, Figure 4, and Figure 5 and the risk map for measles incidence and immigration in Figure 9.

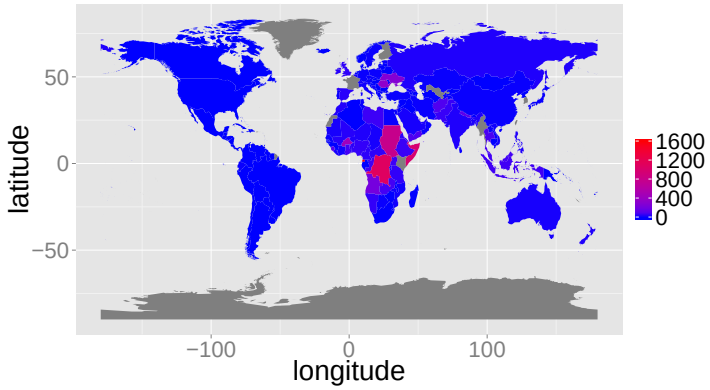

Figure 4: Measles incidence per million 2012

Table 3: Lowest national measles vaccine cover (%, 2012)

country	cover
Equatorial Guinea	34
Somalia	49
Lesotho	60
Central African Republic	65
Papua New Guinea	67
Chad	69
Haiti	69
South Sudan	70
Gabon	71
Yemen	71
Benin	72
Lao People's Democratic Republic	72
Togo	72
Suriname	73
Timor-Leste	73
Paraguay	74
Mauritania	75
Namibia	76
Eritrea	77
Marshall Islands	78
Nigeria	78
Syrian Arab Republic	78
Ukraine	79
Congo	80
Ethiopia	80
Liberia	80
Afghanistan	81
Cameroon	82
Mozambique	82
Senegal	82

Table 4: Measles incidence per million (2012)

country	incidence
Equatorial Guinea	1617
Nauru	1100
Democratic Republic of the Congo	1096
Somalia	979
Djibouti	824
Sudan	786
Burkina Faso	447
Romania	342
Ukraine	280
Sudan	229
Angola	214
Monaco	132
Nepal	122
Sierra Leone	113
Afghanistan	93
Yemen	91
Lesotho	87
Qatar	78
Thailand	78
Malaysia	64
Zambia	64
Ghana	64
Indonesia	63
Congo	60
Uganda	56
Libyan Arab Jamahiriya	52
Ethiopia	47
Pakistan	45
Myanmar	41
Nigeria	38

Table 5: Total New Zealand traveller numbers by country (New Zealand nationals and immigrants, 2012)

country	immigration
Australia	1799655
United Kingdom	401737
China	322076
United States	316058
Fiji	151443
India	107618
Japan	106716
Germany	96308
Korea, Republic of	87419
France	85948
Canada	75381
Samoa	70567
Malaysia	70366
Thailand	61358
South Africa	45980
Tonga	44477
Singapore	42580
Philippines	39747
Netherlands	39151
Hong Kong	37323
Indonesia	35352
Taiwan	34275
Ireland	31396
Italy	25208
Viet Nam	18574
Switzerland	18431
Brazil	17878
Vanuatu	16261
Spain	15604
Sweden	15479

Table 6: New Zealander travel numbers (2012)

country	immigration
Australia	989880
United States	121620
Fiji	104720
United Kingdom	95560
Cook Islands	71960
China	66040
Samoa	46020
Thailand	41100
India	38580
Canada	20400
Japan	20040
Malaysia	19860
Indonesia	19660
Hong Kong	18220
Tonga	17760
Singapore	17120
South Africa	15380
Philippines	15220
France	14500
Korea, Republic of	13960
Viet Nam	12920
Germany	12700
Vanuatu	12520
Italy	11820
Taiwan	10460
New Caledonia	7340
Ireland	6360
French Polynesia	6360
Papua New Guinea	6140
Netherlands	5720

Table 7: Non-New Zealander travel and immigration numbers (2012)

country	immigration
Australia	809775
United Kingdom	306177
China	256036
United States	194438
Japan	86676
Germany	83608
Korea, Republic of	73459
France	71448
India	69038
Canada	54981
Malaysia	50506
Fiji	46723
Netherlands	33431
South Africa	30600
Tonga	26717
Singapore	25460
Ireland	25036
Samoa	24547
Philippines	24527
Taiwan	23815
Thailand	20258
Hong Kong	19103
Indonesia	15692
Switzerland	14851
Brazil	14778
Sweden	13719
Italy	13388
Spain	10104
Denmark	10056
Russia	8103

Table 8: Risk of measles importation to New Zealand due to New Zealand travellers in 2012

country	risk
Australia	8546036
Thailand	3198274
United Kingdom	3184166
Malaysia	1268758
Indonesia	1232849
India	580816
China	293759
Samoa	243492
Philippines	241740
Nepal	188450
Romania	164376
Ireland	148715
Spain	141632
Singapore	135591
Ukraine	100781
Viet Nam	82248
Sudan	78640
Afghanistan	74756
Italy	72995
United Arab Emirates	60508
Pakistan	58435
Nauru	44000
Democratic Republic of the Congo	43850
Qatar	43686
Israel	40301
Japan	35977
Russia	35334
Angola	34258
Switzerland	27308
Saudi Arabia	25775

Table 9: Risk of measles importation to New Zealand due to non-New Zealander travel and immigration in 2012

country	risk
United Kingdom	10202161
Australia	6991116
Malaysia	3226580
Thailand	1576414
China	1138900
India	1039356
Indonesia	984022
Ukraine	664315
Ireland	585413
Romania	490731
Philippines	389563
Spain	260191
Singapore	201644
Germany	167620
Japan	155607
Nepal	136076
Israel	133876
Samoa	129878
Russia	120298
Switzerland	113281
Pakistan	90079
Somalia	85191
Italy	82679
Nauru	82500
Sudan	62912
Saudi Arabia	56809
Belgium	53337
Sweden	43273
Afghanistan	37098
Viet Nam	35993

Table 10: Risk of measles importation to New Zealand in 2012, all travellers

country	risk
Australia	15537152
United Kingdom	13386328
Thailand	4774688
Malaysia	4495338
Indonesia	2216871
India	1620172
China	1432659
Ukraine	765096
Ireland	734128
Romania	655107
Philippines	631303
Spain	401823
Samoa	373370
Singapore	337236
Nepal	324526
Germany	193081
Japan	191585
Israel	174177
Italy	155674
Russia	155632
Pakistan	148514
Sudan	141552
Switzerland	140589
Nauru	126500
Viet Nam	118241
Afghanistan	111854
Somalia	104775
Saudi Arabia	82584
United Arab Emirates	67606
Belgium	63784

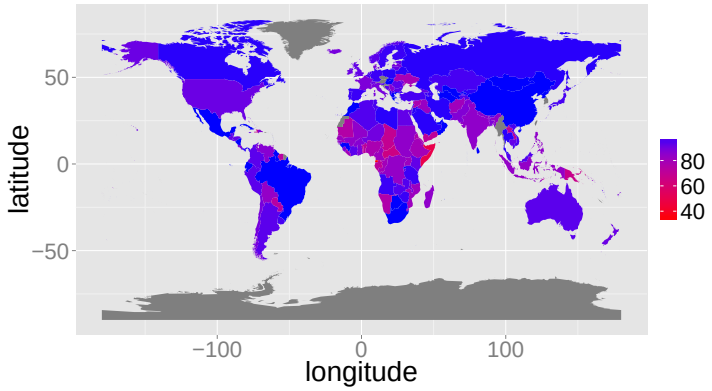

Figure 5: Measles vaccination cover (%) 2012

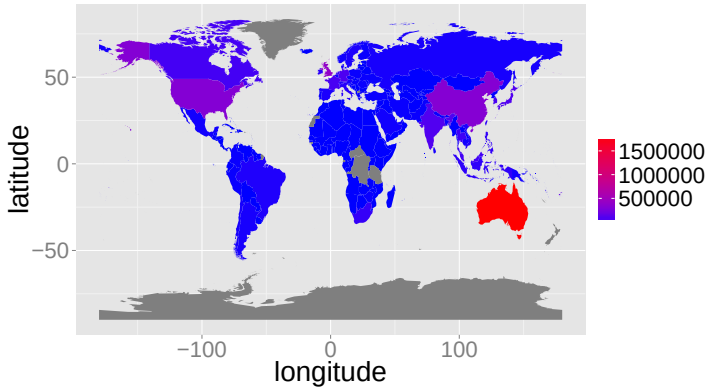

Figure 6: Total international travel, 2012

Though global incidence of measles in declining, in recent years that decline has slowed (Figure 12) and immigration rates to New Zealand have risen (Figure **??**). This suggests that the risk of measles importation could increase, though further analyses are require to understand the interaction between these variables. Of note, however, is the clear seasonality in immigration (Figure **??**). This seasonality suggests that there may be period of increased risk of measles importation, though again the interactions with seasonal measles transmission from the nations of origin will be an important factor in determining the risk of measles importation.

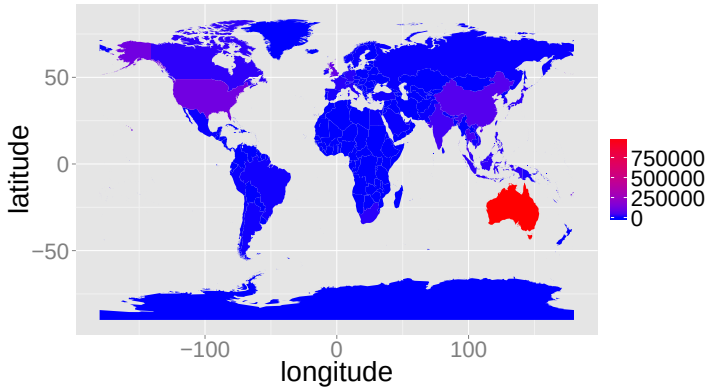

Figure 7: New Zealander international travel, 2012

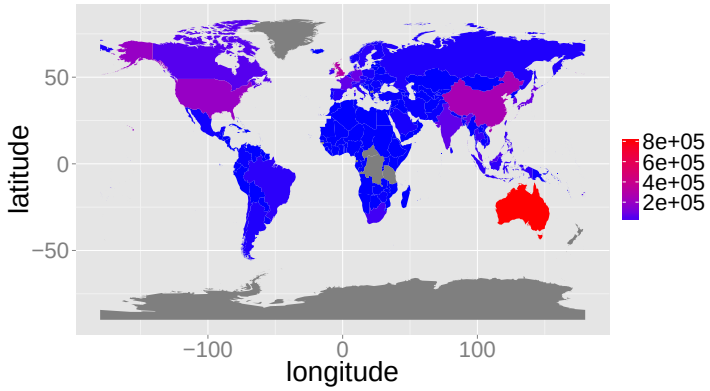

Figure 8: Non-New Zealander international travel and immigration, 2012

4.4 Regression analyses results

The distribution of the cases per category used in the regression analyses are in Figure 19.

The predicted values from the regression model plotted against the reported cases are shown in Figure 20, and the residuals are shown in Figure 21.

The significance of the different predictor variables can be seen in the ANOVA results:

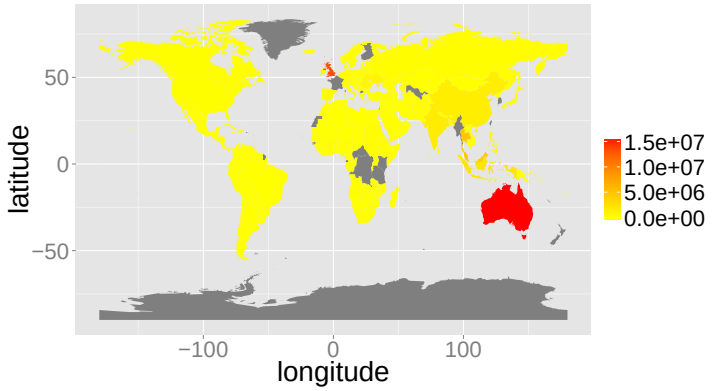

Figure 9: Risk map for measles importation, 2012

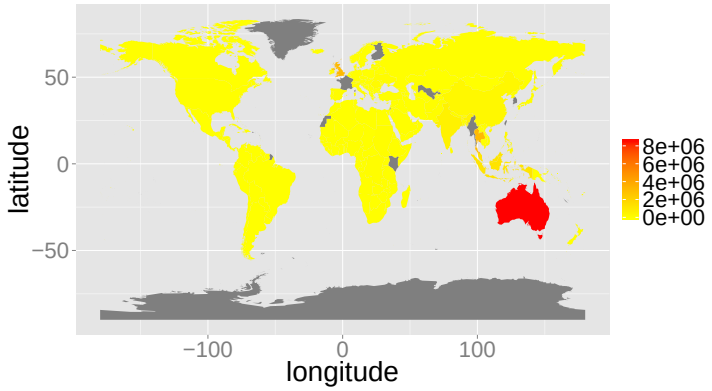

Figure 10: Risk map for measles importation from New Zealander international travel, 2012

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			39	1453.62		
Age	4	1304.20	35	149.43	183.58	0.0000
Ethnicity	3	20.00	32	129.43	3.75	0.0285
NZDep	1	10.70	31	118.74	6.02	0.0239
Age:Ethnicity	12	81.91	19	36.83	3.84	0.0045

A summary of the regression model (Equation 1) with the individual effects and the statistical support for the estimated coefficients can be seen here:

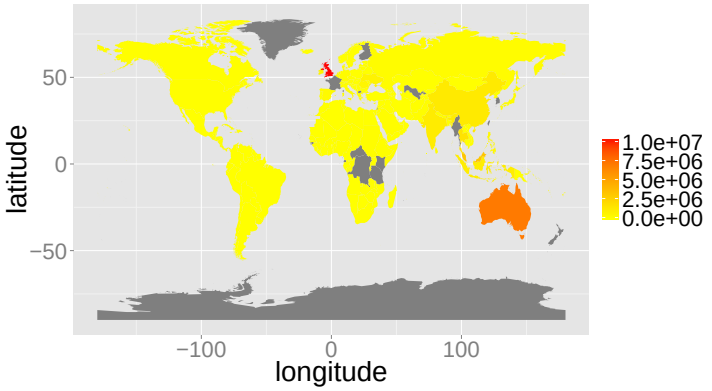

Figure 11: Risk map for measles importation from non-New Zealander international travel and immigration, 2012

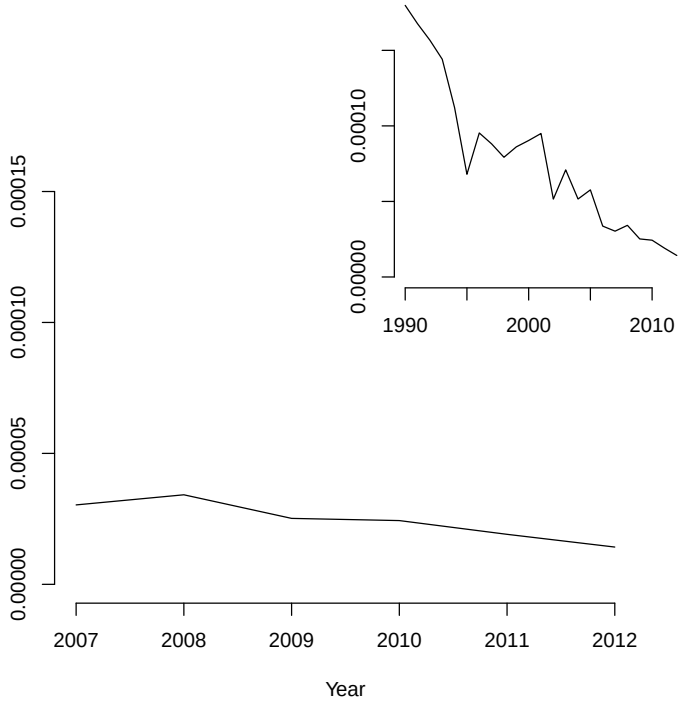

Figure 12: Trend in global per capita measles incidence

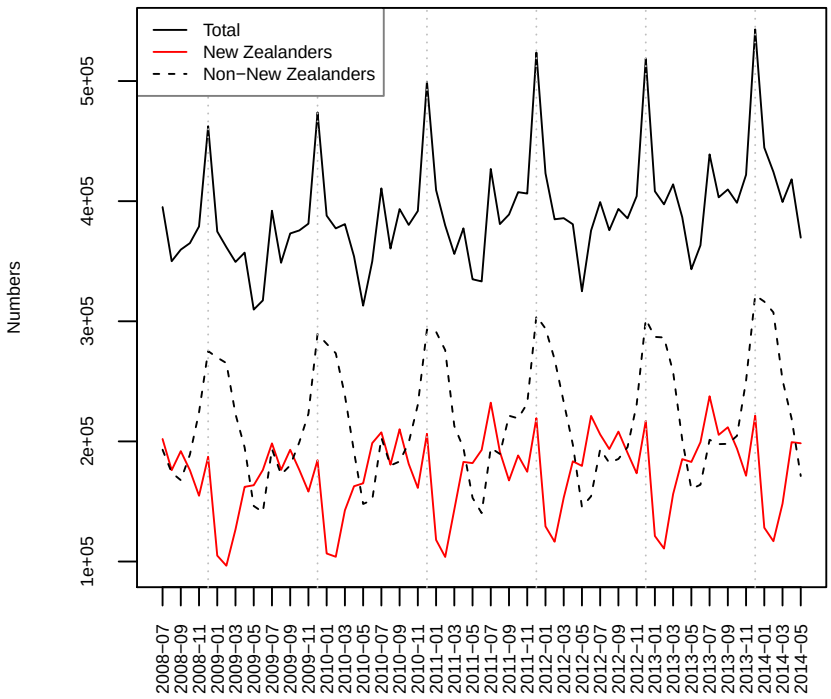

Figure 13: Trends in international travel

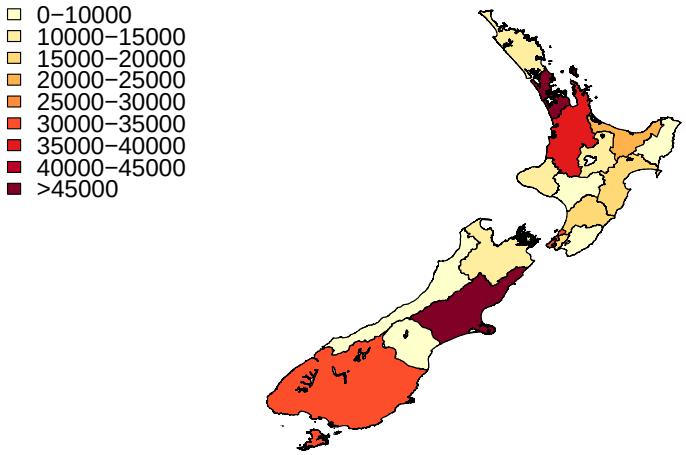

Figure 14: Numbers of naive individuals per District Health Board

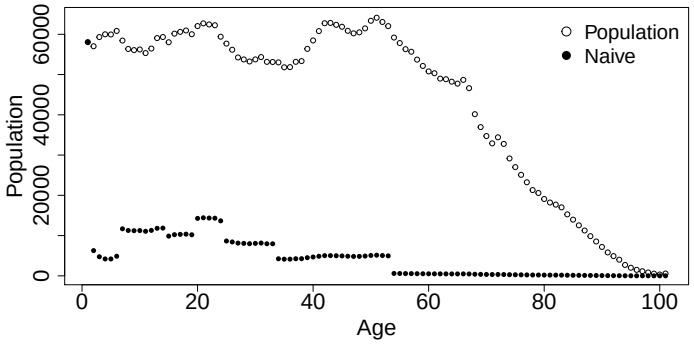

Figure 15: New Zealand population by age and estimated numbers of naive people in each age class

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-6.4674	0.1148	-56.32	0.0000
Age3-5	-0.9129	0.2054	-4.44	0.0003
Age6-17	-0.7618	0.1343	-5.67	0.0000
Age18-24	-1.5050	0.1937	-7.77	0.0000
Age25+	-2.9507	0.1608	-18.35	0.0000
EthnicityAsian	0.0530	0.3250	0.16	0.8721
EthnicityMaori	0.2124	0.1994	1.07	0.2999
EthnicityPacific	1.1603	0.2043	5.68	0.0000
NZDep6-10	-0.2119	0.0855	-2.48	0.0227
Age3-5:EthnicityAsian	-2.0315	1.3827	-1.47	0.1581
Age6-17:EthnicityAsian	-1.0074	0.4717	-2.14	0.0459
Age18-24:EthnicityAsian	-0.8311	0.5941	-1.40	0.1779
Age25+:EthnicityAsian	0.4211	0.4433	0.95	0.3541
Age3-5:EthnicityMaori	-0.3864	0.4096	-0.94	0.3573
Age6-17:EthnicityMaori	-0.0855	0.2469	-0.35	0.7328
Age18-24:EthnicityMaori	-0.5828	0.4484	-1.30	0.2092
Age25+:EthnicityMaori	-1.0482	0.5242	-2.00	0.0600
Age3-5:EthnicityPacific	-2.1316	0.8139	-2.62	0.0169
Age6-17:EthnicityPacific	-1.4541	0.3347	-4.35	0.0003
Age18-24:EthnicityPacific	-0.9827	0.5129	-1.92	0.0705
Age25+:EthnicityPacific	-0.6127	0.4367	-1.40	0.1767

Apart from over-representation of some MLA categories discussed above and not included here, the results of the regression model suggest that age is a strong predictor of being a measles case. Indeed, all age categories are significantly less

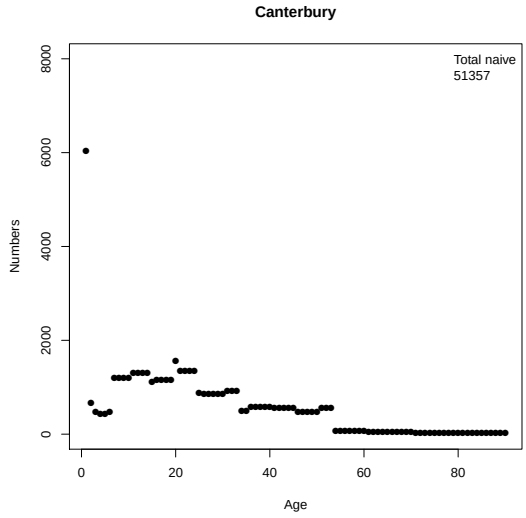

Figure 16: Numbers of naive individuals per age class, Canterbury District Health Board

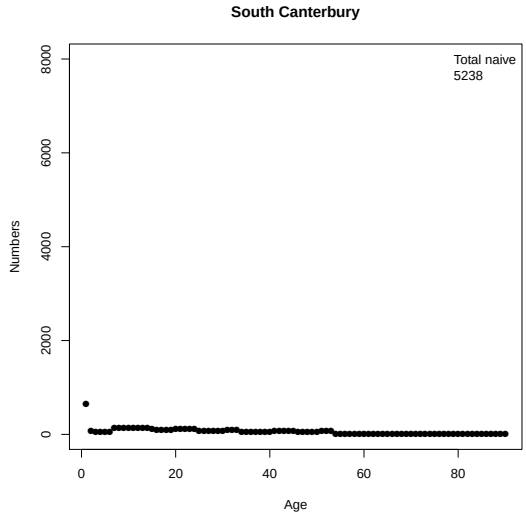

Figure 17: Numbers of naive individuals per age class, South Canterbury District Health Board

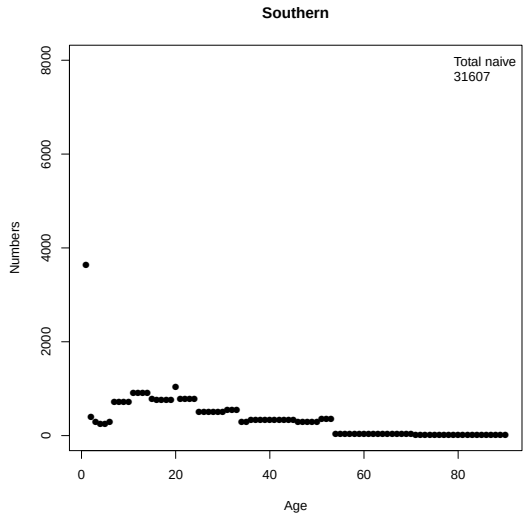

Figure 18: Numbers of naive individuals per age class, Southern District Health Board

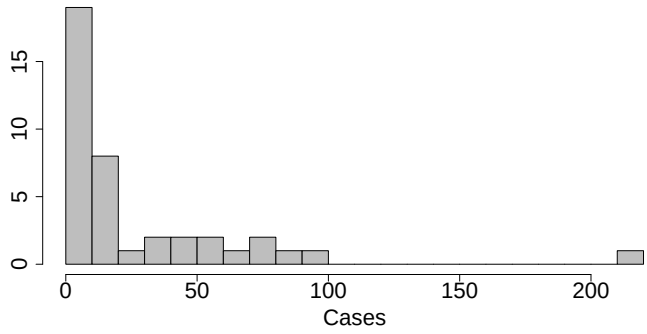

Figure 19: Distribution of cases per category used in the final regression model

likely to be measles cases compared to 0-2 year olds, and the likelihood decreases with age (Figure 2).

People of Pacific origin are also over-represented (β = 1.16, standard error (SE) = 0.2, p–value < 0.0001), NZDep levels 6-10 under-represented (β = -0.21, SE = 0.085, p–value = 0.02), and there are some other age:ethnicity classes that are significantly less represented in the data compared to Europeans in those ages classes, particularly in the 6–17 age classes. In later outbreaks (since 2007)

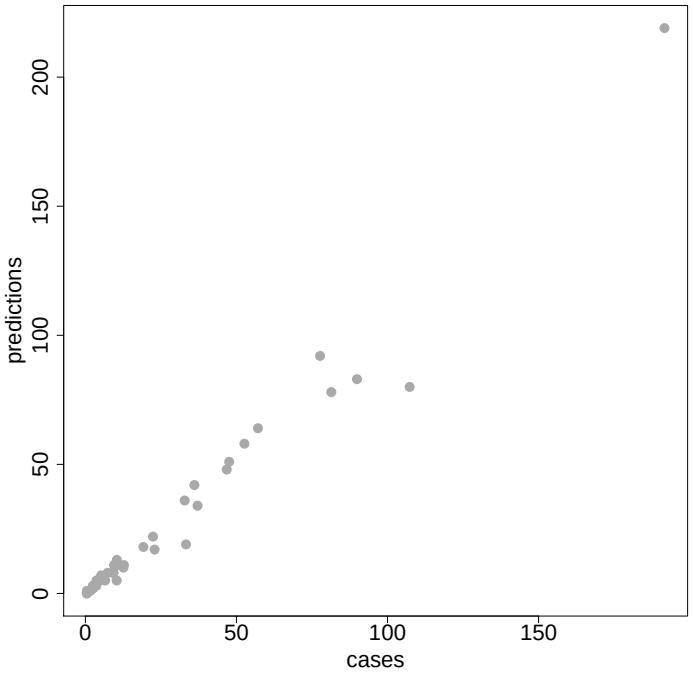

Figure 20: Regression model (Equation 1) predictions plotted against the cases (Table 2)

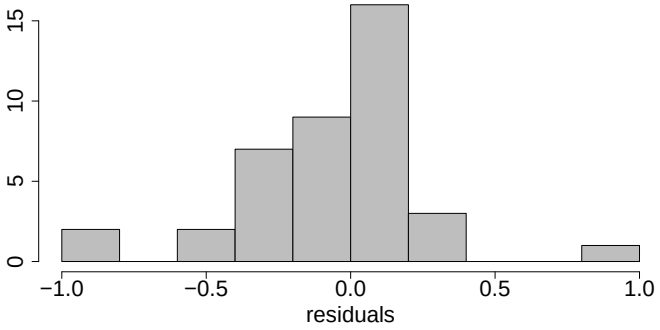

Figure 21: Histogram of residuals from the regression model (Equation 1)

there has been a shift in the distribution of ages infected. The very young are still most likely to be infected, but of school aged children older teenagers are more likely to be represented then the under tens (Figure 2). This pattern suggests that improving vaccination coverage in the young is reducing the burden of measles in those age categories. Interestingly the regression results suggest risk of measles cases in the 6–17 year age category was greater for Europeans and Maori.

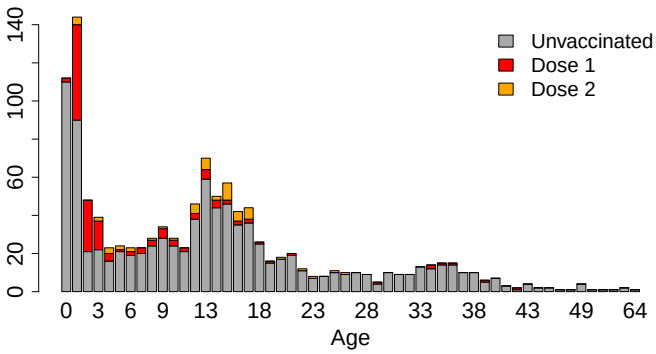

Figure 22: Age and vaccination status of cases

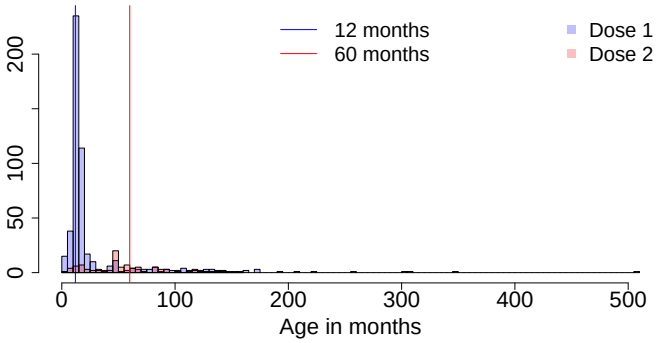

Figure 23: Age of vaccination of vaccinated measles cases

4.5 Risk analysis discussion

The regression analyses suggest that age is a particularly strong risk factor for measles. This comes as no surpise to epidemiologists or health care providers.

However, our analyses also highlight other groups that are at greater risk of measles. In particular, Pacific people are at greater risk, as are the more wealthy (NZDep 1–5), and European and Maori 6–17 year old children compared to Asian and Pacific ethnicity children of the same age. Interpretation of these results must still be viewed with some caution, however, as there is very likely a spatial effect that might not be accounted for in these analyses. Additional data we have been provided by the Ministry of Health but are yet to incorporate in our risk analyses are finer scale (domicile level) immunisation coverage data from the National Immunisation Register (NIR). A key issue with incorporating spatial immunisation data has been the denominator data, and how to deal with people of greater age than those recorded in the NIR. These analyses are possible future directions for this work. The results of these regression analyses are also discussed in the benefit–cost section below (Section 7.2)

4.6 Future risk analyses

We received the raw EpiSurv measles case data from The Institute of Environmental Science and Research Ltd (ESR) on 27 June 2014. Initial analyses of those data (not shown) suggest that we require denominator data to perform multivariate analyses to avoid confounding results due to a lack of independence among risk factors. Specifically for the multivariate analyses we wish to perform that detect interactions we require $\mathsf{Age} \times \mathsf{Prioritised\ Ethnicity} \times \mathsf{NZDep}$ data for New Zealand to test whether interactions among case covariates provide additional information on risk over the univariate analyses performed in the report reviewed above. These $\mathsf{Age} \times \mathsf{Prioritised\ Ethnicity} \times \mathsf{NZDep}$ data only became available to us on 3 July 2014, provided by the University of Otago.

The following analyses are in progress, for inclusion in later reports:

- Multivariate regression analyses to assess interactions between risk factors that may confound the univariate analyses.
- Update of the importation risk analyses using a broader range of years, including modelling the trend in importations.

Additional data we believe would enable us and the Ministry to better understand measles risk is fine scale (lower than District Health Board (DHB)) immunisation coverage data. We understand the National Immunisation Register (NIR) allows tracking of the vaccination status of children and this is very useful, but inclusion of these data at lower (e.g. meshblock, census area unit) level would allow better understanding of risk of measles infection and resource allocation because they may allow targeted immunisation programmes. Thus the data gap that we have that will hinder us providing fine scale risk maps is:

- Meshblock (or census area unit) level immunisation coverage data to allow targeted immunisation and understanding of risk at a fine scale level.

An additional data set that would enable us to develop the understanding of measles importation risk is:

- The number of New Zealanders arriving from abroad each year, the countries to which they travelled, and length of travel.

4.7 Risk analysis summary

- There is a continued, and perhaps increasing, risk of measles importation due to travel and endemic measles elsewhere in the world.
- There may be seasonal changes in risk of measles importation, though further analyses are needed.
- Risk of measles infection decreases significantly with age
- Pacific people are statistically more at risk of measles infection
- There is some statistical support for those living in better socio-economic situations being at greater risk of measles
- There is some statistical support for Pacific and Asian children in the 6–17 year age categories being at lower risk than European or Maori children

5 Modelling measles epidemics

A previously-published model of the dynamics of measles infections in New Zealand has been used to evaluate the vaccination strategy in New Zealand of MMR1 at 15 months and MMR2 before 5 years [29, 28, 34]. The results show that achieving coverage of greater than 90% at both vaccination opportunities is necessary if future epidemics of measles are to be prevented.

The original mathematical model for the dynamics of measles in New Zealand prepared in 1996 [34] successfully predicted the 1997 epidemic, which was curtailed by a mass vaccination campaign [23, 29]. Subsequent extension of this work in 1998 showed that the then current schedule of MMR1 at 15 months and MMR2 at 11 years was insufficient to prevent further epidemics. The model developed by [29] supported the change in the immunisation schedule that took effect in January 2001, at which time MMR2 was changed from delivery at 11 years to delivery before the age of five. The schedule was changed in 2000 with MMR2 now being administered before 5 years [3] and later analyses suggested high levels of vaccination coverage (but less than 95%) could eliminate measles, but emphasised that it is necessary to maintaining high coverage rates in order to prevent future epidemics [28].

These results were comparable to others, for example: [5] suggested two-dose schedule for England and Wales, with the second vaccination given at age four; and [17] recommended a second vaccination at either 18 months or five years, to complement the first vaccination at 12 months in Canada. In addition, [1] found that vaccinating 85% of susceptible children aged one to seven years at five-yearly intervals would prevent epidemics in Israel. All agree that two vaccinations at no less than five years apart are necessary to prevent measles

epidemics. [35] took existing policies in eight European countries and estimated the coverage rates required to reduce R_v below one. They found that results depended on the age at delivery, but no strategy succeeded if coverage rates were below approximately 87%.

Numerous models for measles vaccination strategies for various regions [1, 5, 14, 17, 35] based on sets of nonlinear differential equation (ODE) models have reached similar conclusions. The differences in the models have been in the details of the representation of the infectious period, and in the ways in which the age and contact structures of the population have been specified. While analyses suggest that 85% coverage at MMR1 and MMR2 could be sufficient to prevent future measles epidemics, [18] in the Netherlands showed that high overall levels of measles vaccination can obscure pockets of poor coverage, resulting in localised regions with increased risk of infection and effective immunisation is difficult to evaluate.

The quantity that determines whether an epidemic will occur is the basic reproduction number of the infection, R_0. This is defined as the expected number of secondary infections that would arise from a single primary infection introduced into a fully susceptible population [2, 12]. If $R_0 > 1$ an epidemic will occur following an introduction of infection. The best estimate for measles in New Zealand was $R_0 = 12.8$ [28]. The basic reproduction number of the infection under vaccination, R_v, is the expected number of secondary infections that would arise from a single primary infection introduced into a vaccinated population at equilibrium and is a robust indicator of the performance of a vaccination schedule. If $R_v < 1$ epidemics are prevented. The case reproduction number of the infection at time t, R_t, is the expected number of secondary infections that arise from a single infection at a particular time and depends on the number in the population who are susceptible.

5.1 Modelling methods

To understand the level of immunity in the population, the transmission dynamics of measles in the partially immune population and how likely an outbreak was of becoming endemic, we estimated R_v from all the outbreaks in New Zealand since 2009. To do this we estimated R_t, following an adaptation of the methods in [25, 36]. We were required to compute the generation time for measles to do so. The generation time is the average time an index case infects others after becoming infected. We used a lognormal distribution with mean 12.0 and standard deviation (s.d.) 3.5 from [20]. We then estimated R_t from the incidence data for each outbreak, defining outbreaks in the dataset given their temporal and geographic correlations (Figure 24). The outbreaks we used in our analyses are shown in Figure 25.

To estimate the proportion of the population requiring vaccination utilising our estimates of R_v, we make several simplifying assumptions regarding the relationship between the proportion requiring vaccination, p_c, and R_0. Specifically,

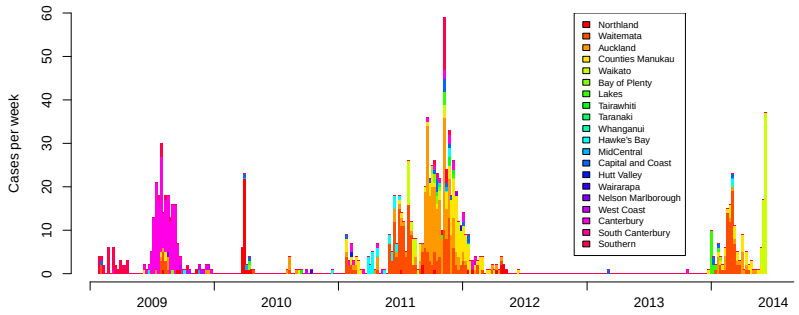

Figure 24: Measles cases by district health board (DHB) from 2009 to 2014

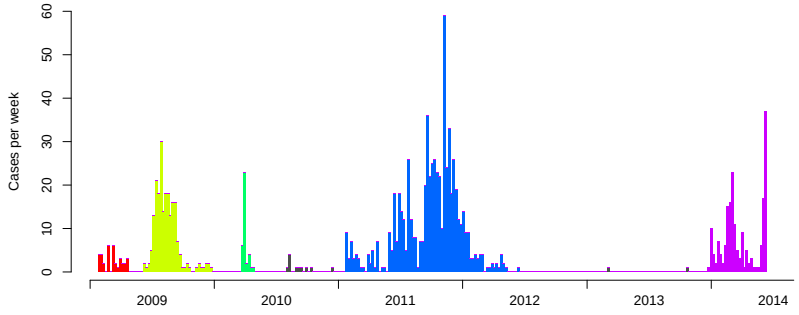

Figure 25: Measles data classified as outbreaks for reproductive number of the infection (R_v) estimation

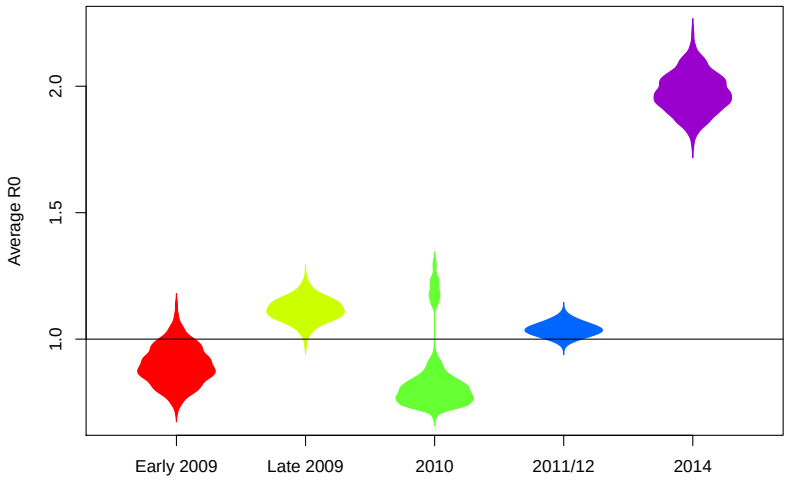

Figure 26: Estimates of R_v (Average R_0) for the outbreaks each year, as classified by outbreaks in Figure 25

we use the simple relationship:

$$p_c = 1 - (1/R_0) \tag{2}$$

To account for the different outbreak sizes we weighted our R_v estimates by outbreak size and used 1.96 standard deviations of the mean of our R_v estimates, to generate 95% confidence limits from 2009–2014 outbreaks or the 2013–2014 outbreak for our modelling scenarios below.

We then assume that the measles epidemics are occurring in a naive population that is the size of the naive and currently susceptible population remaining in New Zealand and thus R_0 is equivalent to R_v. We estimated the susceptible population in New Zealand from the national level vaccination coverage data provided by the Ministry of Health for this work (approximately 11%, Figure 15). Thus, the p_c applies to the naive population in New Zealand and these are the additional vaccinations required to reduce R_v to one in the overall New Zealand population.

We then used the proportions of the population that were estimated to require vaccination (p_c, Equation 2), and the proportions of the naive population per age case from Figure 15 to provide different scenarios to achieve those goals. These are explored and discussed in relation to the risk analyses (Section 4.4) in the benefit–cost analyses section below (Section 7.2).

Finally, we used the same model structure and generation times to estimate

the epidemic sizes once vaccination catch up protocols had been implemented assuming $R_v < 1$ and the population of susceptible people in New Zealand was now reduced by the numbers vaccinated. Because the model is stochastic, we ran 1000 simulations and report the mean values, though the distribution of these is shown in the benefit–cost section (Section 7.2).

6 Mick Introduction

The well-known equation for the final size of an epidemic in a homogeneously mixing susceptible population is [13]

$$\log(1-\mathcal{P}) + \mathcal{R}_0\mathcal{P} = 0$$

where $\mathcal{R}_0$ is the basic reproduction number and $\mathcal{P}$ is the proportion of the population infected over the course of the outbreak. If a proportion x_0 of the population is susceptible following vaccination, then the reproduction number under vaccination is $\mathcal{R}_V = x_0\mathcal{R}_0$, and the final size equation becomes

$$\log\left(1-\frac{\mathcal{P}}{x_0}\right) + \mathcal{R}_0\mathcal{P} = 0$$

Hence the relationship between the proportion initially susceptible and the proportion infected in an epidemic is

$$x_0 = \frac{\mathcal{P}}{1-e^{-\mathcal{R}_0\mathcal{P}}}$$

In order to prevent future epidemics, it is necessary that $\mathcal{R}_V < 1$. Hence, the proportion of the population that must be vaccinated to prevent future outbreaks is $x_0 - 1/\mathcal{R}_0$.

These formulae were applied at a District Health Board (DHB) level, assuming no mixing between DHBs.

6.1 Modelling results and discussion

The estimated R_v for each outbreak is shown in Figure 26. The probability density of the R_v estimates for each outbreak all include one. Of particular note is the ongoing outbreak, which has an R_v well above one and thus we may expect this outbreak to persist if conditions remain the same. An important caveat to this outbreak analysis is that because this 2013–2014 outbreak is an ongoing outbreak, and not in decline, R_0 is necessarily over one, and so the comparison with others must be cautious.

These analyses also imply that the regular (approximately yearly) importation of measles is an ongoing process. Given the risk of importation of measles as highlighted in section 4 is likely to continue, these analyses suggest substantial efforts are required to maintain the level of immunisation to high enough levels that measles does not become endemic. The measles outbreak in 2011–2012

had an R_v of just greater than one, and yet it persisted for over 12 months. This implies that the current outbreak may persist within the population for a substantial period, given it's R_v is approximately twice that of the 2011-2012 outbreak. A caveat to this and other R_v estimates is that the 2013–2014 outbreak may include some sporadic cases and thus the true basic reproductive numbers may be lower than estimated. However, sub-clinical and underreporting may lower the estimate. The relative contributions of both to our estimates are currently unknown.

The estimated R_v for each outbreak is shown in Figure 26 and in the previous interim report. The probability density of the R_v estimates for each outbreak all include one, except for the ongoing 2013–2014 outbreak, which has an R_v well above one. As discussed in the previous interim report, the important caveat to this outbreak analysis is that because this 2013–2014 outbreak is an ongoing outbreak, and not in decline, R_v is necessarily over one, and so the comparison with others must be cautious. However, the results of these differences are presented and discussed in the benefit–cost analysis section (Section 7.2). The 95% confidence intervals for our analyses suggest the R_v for the 2009–2014 outbreaks is 0.92–1.19, and for the current outbreak 1.82–2.13.

The regularity of these outbreaks also imply that the regular (approximately yearly) importation of measles is an ongoing process. Given the risk of importation of measles as highlighted in section 4 and our previous report is likely to continue, we explore the effects of this in the benefit–cost section (Section 7.2).

The measles outbreak in 2011–2012 had an R_v of just greater than one, and yet it persisted for over 12 months. This implies that the current outbreak may persist within the population for a substantial period, given it's R_v is approximately twice that of the 2011-2012 outbreak. A caveat to this and other R_v estimates is that the 2013–2014 outbreak may include some sporadic cases and thus the true basic reproductive numbers may be lower than estimated. However, sub-clinical and underreporting may lower the estimate. The relative contributions of both to our estimates are currently unknown.

To use the results from our modelling exercise to help inform the appropriate measles vaccination coverage, we use Equation 2. Depending on R_v the proportion of the national population requiring additional vaccination to make $R_v < 1$ ranged from 0 ($R_v = 0.92$, lower 95% confidence limit) to an upper 95% confidence limit of 53% for the 2013–2014 outbreak ($R_v = 2.13$, Figure 26). These additional vaccination numbers can be made up in a number of different ways, and these are discussed in the benefit–cost section (Section 7.2).

The results of these modelling exercises suggest vaccination levels are close to eliminating the possibility of endemic measles transmission, as estimates of R_v typically include 1 (Figure 26). However, the naive population (Figure 15) and the higher R_v for the 2013–2014 outbreak (Figure 26) suggests that catch up vaccination may be necessary. Researchers found that vaccinating 85% of susceptible children aged one to seven years at five-yearly intervals would prevent epidemics in Israel [1], but nearly all other studies in Europe suggest no strategies succeeded if coverage rates were below approximately 87%, which the population level immunity in New Zealand has only just reached. Measles vacci-

nation in various regions [1, 5, 14, 17, 35] based on sets of nonlinear differential equation (ODE) models suggest that 85% coverage at MMR1 and MMR2 could be sufficient to prevent future measles epidemics, but [18] showed that in the Netherlands high overall levels of measles vaccination can obscure pockets of poor coverage, resulting in localised regions with increased risk of infection and effective immunisation is difficult to evaluate.

DHB	Size	Naïve	Attack	Vacc
Auckland	436350	52010	31159	17920
Bay of Plenty	206000	20679	8437	4585
Canterbury	482180	51357	24695	13687
Capital and Coast	283700	32625	18403	10461
Counties Manukau	469300	55544	32903	18880
Hawke's Bay	151700	15602	6846	3751
Hutt Valley	138380	15198	7836	4388
Lakes	98196	10558	5192	2886
MidCentral	162560	17328	8348	4628
Nelson Marlborough	137000	13059	4411	2356
Northland	151690	14921	5688	3071
South Canterbury	55620	5238	1678	893
Southern	297420	31607	15115	8371
Tairawhiti	43650	4769	2431	1359
Taranaki	109750	11473	5262	2899
Waikato	359310	39402	20248	11331
Wairarapa	41112	3932	1346	720
Waitemata	525550	58350	30774	17291
West Coast	32151	3197	1265	685
Whanganui	60120	6075	2530	1378
TOTAL	4241739	462924	234567	131539

Table 11: Size: DHB Population, Statistics NZ 2013; Naïve: DHB naïve population ($x_0 \times$ Size); Attack: Number infected in DHB in an outbreak of measles ($\mathcal{P}$); Vacc: Number to be vaccinated in DHB to reduce $\mathcal{R}_V$ below one ($(x_0 - 1/\mathcal{R}_0) \times$ Size).

6.2 Summary of modelling

- Regular introductions of measles pose an ongoing threat to New Zealand's efforts to eliminate measles (also see section 4).
- The reproduction number for measles in a partially immune population is often close to one, suggesting increased population level immunity is required to prevent this measles persisting.
- The reproduction number, R_v, for measles in the current outbreak is well

over one, suggesting that this outbreak has the potential to persist for prolonged periods, with the caveat that this estimate was made during the ongoing outbreak.

- The reproduction number for measles in a partially immune population is often close to one, suggesting increased population level immunity is required to prevent this measles persisting.
- The reproduction number, R_v, for measles in the current 2013–2014 outbreak is well over one, suggesting that this outbreak has the potential to persist for prolonged periods within the population is it circulating.
- Additional vaccination levels to push R_v below one among the currently naive population in New Zealand range from 0% ($R_v < 1$) to 53% (R_v 2.13, approximately 250,000 vaccinations), depending on the appropriate reproduction number, R_v, for measles in New Zealand.

6.3 Future modelling

Future modelling we aim to perform are:

- An update of previous ODE models of measles in the overall population according the differing vaccine coverage scenarios [28].
- Model measles outbreaks with differing scenarios of measles importation into various population groups based on current introduction rates.

7 Cost analyses

In this section we provide a review of the costs of measles from other locations and an analysis of the costs involved with the current measles outbreak.

Approximately 50 years ago, approximately 135 million cases and 7–8 million deaths were believed to occur in the world due to measles [9]. Thirty years later, it was estimated there were still approximately 45 million cases of measles occurring annually, including 6 million measles-related fatalities. [38] estimated that in 1999 measles was responsible for more than 30 million disability adjusted life years (DALYs) lost and 12 million in 2005. Similarly, the number of cases was reduced by more than 50% from 43 million in 1999 to approximately 20 million in 2005. They estimated approximately 7.5 million deaths from measles were avoided from 2000–05 due vaccination. The World Health Organization (WHO) estimated 158,000 deaths from approximately 355,000 measles cases in 2011 [39]. In addition to the substantial losses occurring in measles-endemic countries, a significant impact is felt in heavily measles-vaccinated countries, which may be considered measles-free, due to contact with cases either in the country of origin or in the previously measles-free country.

The annual cost of treating and controlling measles in 11 industrialised countries was estimated to cost more than US$150 million [8]. The estimated cost

for a case ranged from US$189–344 [8]; however, the average estimated cost of a typical hospital case ranges from US$967–1,755 [7]. [32] estimated the economic benefits from cases averted due to measles vaccination. They estimated that the expanded vaccination from 2005 to 2015 in 72 of the world's poorest countries could result in nearly US$10 billion of costs averted between 2011 and 2020. Ninety-nine percent of these averted costs were the result of lost productivity due to an estimated 360,000 measles-specific premature mortalities, with the remaining <1% associated with averted treatment costs and reduced caretaker productivity for the nearly 12 million measles cases avoided.

Italy has the highest reported annual cost of measles among industrialised countries [8]. In 2001, it reported losses related to measles of approximately US$50 million. The economic impact of a large measles outbreak in Italy, 2002–03 examined the costs associated with 5,154 hospitalisations where measles was the main discharge diagnosis. The mean length of hospital stay was 5.2 days (median = 4 days and range = 1 to 303 days). The total cost of these hospitalisations amounted to €8.83 million (€1 ≈ NZ$2.0 in 2002-03), or approximately €1,700 per case. The average cost per non-complicated measles case was €1,429, while the mean cost of a case with complicated measles was €2,721. The average daily cost of a hospital stay was €327.

An outbreak of measles occurred in Sydney, Australia, lasting nearly 2 months in 2011 and resulted in 26 confirmed cases [16]. Seven (27%) of the cases required hospitalisation for more than 1 day and 10 (38%) resulted in management within a hospital emergency department. During this outbreak, a total of 1,395 contacts were identified and managed by a public health unit in western Sydney. The mean number of contacts per case was 54 (median = 28, maximum = 206). The estimated cost to the public health unit for contact management for the epidemic was in excess of AUS$48,000, with 90% of this being associated with staff time.

Germany implemented a two-dose measles vaccination program in 1991 and has seen the benefits in recent years. In 2001 more than 6,000 cases were reported in Germany but by 2004 this number fell to 122 [37]. However, in 2005 more than 500 cases were reported by the middle of the year in two German states, with the vast majority (>95%) in non-vaccinated children [31]. An economic analysis was performed of the 614 measles cases reported in an 8-month period in Duisburg in the state of North Rhine-Wesphalia (NRW). In that study, they estimated the health-care provider costs to be approximately €229,000, or €373 per case. Approximately 78% of these costs were associated with the 95 (15.5%) of the cases that were hospitalised. The mean costs of the hospitalised patients was €1,877, including one patient with encephalitis at a cost of €35,623. In addition to the health-care provider costs, additional costs of €89,400 were incurred by the district public health office, the majority (€85,000, 95.1%) for personnel, €2,300 (2.6%) for vaccination, and €2,100 (2.3%) for serologic testing. Therefore the combined direct costs of these 612 cases amounted to €318,400, or €520 per case. In addition, to determine the total impact, it would be necessary to include the indirect losses associated with lost production of cases and care givers.

Although measles was declared eliminated from the United States in 2000, it remains a concern due to the endemic nature of it around the world [26]. Several studies have been conducted in the United States to assess the economic impact of recent measles outbreaks due to imported measles. [24] estimated the economic impact to public health departments in the US as the result of 16 outbreaks in 2011. The outbreaks lasted an average of 22 days and resulted in 107 confirmed cases; however, from these 107 cases, they estimated between approximately 8,900 and 17,500 contacts with confirmed cases, requiring between 42,600 and 83,100 personnel hours at a cost of between US$2.7 and 5.3 million. Overall, it was estimated that each contact required 4.7 personnel hours at a cost of US$298 per contact. It was estimated that for the one week that the Iowa Department of Public Health (DPH) investigated a case in 2004, 2,525 hours were used to identify contacts, set up vaccination clinics, and institute and enforce quarantine orders for those who refused vaccination [11]. In total, it was estimated the direct costs associated with three cases of measles was US$142,452, or nearly US$50,000 per case.

The impact of a measles outbreak due to a non-autochthonous case in Indiana was also reported [26], and a total of 34 cases, 94% of which were not vaccinated against measles, were reported in the outbreak. Direct cost information was obtained from approximately 100 public health officers and infection-control officials needed to control the outbreak. Direct cost for those completing a survey showed the outbreak cost at least $167,685, 83% of which ($139,023) was for wages, salaries and overhead. This amounted to a direct cost of $4,932 per measles case. These costs did not include either patient care or indirect costs, which would have made the total and per case cost higher.

The direct medical and public health costs in response to a single case of refugee-imported measles has been reported [10]. Costs included labour, translation and benefits for public health workers. In addition, medical costs were incurred due to vaccination, immunoglobulin, testing for measles immunity, hospitalisation, transportation and diagnosis. In total, 387 hours were associated with this single case, resulting in a cost of US$11,881. In addition, per-contact costs amounted to US$264. The cost of hospitalisation for the 3-day stay by the index case was US$931. Additional costs were associated with physician visits (US$294), vaccine and immunoglobulin (US$1,765), mileage (US$205) and immunologic screening tests for the parents' exposed to measles (US$240) for a total of US$23,816.

Economic analyses of measles control programs have shown them to be financially effective. In the Republic of Korea, the economics of alternative measles vaccination programs were compared. All of the alternatives were found to be economically efficient (benefit/cost ratio (B/C) > 1.0), with the alternative using two doses of the MMR program, with a catch-up campaign for measles and rubella being the most favourable (B/C $= 1.27$).

The purpose of the current study is to estimate the cost of the current measles outbreak in New Zealand. Using this information, we will then evaluate the economics of alternative measles control strategies in order to provide additional information to public health officials and decision makers.

7.1 Cost analyses methods

Costs were evaluated as either direct or indirect. Direct costs included physician consultations, hospitalisations, drugs, vaccination, long-term care for chronic sequelae, special education costs. Direct costs can be divided into medical and non-medical [30]. Direct medical costs include costs for diagnosis, treatment, continuing care, rehabilitation and terminal care. Personnel time (investigation and emergency response), materials (phone calls, vaccine), personnel (cost, wages and fringe benefits), overhead costs, public information, and mileage are estimated when calculating direct medical costs. Direct non-medical costs include transportation to and from health care providers.

Indirect costs are productivity losses for the case and/or health care provider, e.g. parent of a school child. Indirect costs included work loss for cases and caregivers. This could also include the economic value of premature life lost, costs associated with permanent disability, e.g. deafness and mental retardation. Commonly the human value approach (HVA) has been used to estimate economic impact of life. The HVA measures the potential future earnings of an individual and discounts it into a present value. Typically this is 3% but 5% has also been used in a sensitivity analysis, which is more compared to non-human life calculations and will tend to reduce the present value of the future earnings (saved by avoiding a case).

Data for the current measles outbreak were obtained from the New Zealand Ministry of Health, from 2008 through June 2014. Data included information on gender of the case, ethnicity and age of the case at discharge from hospital, days spent in the hospital, year of case, number of events, case weight and associated cost.

Cost of the Auckland Regional Public Health Service (ARPHS) for measles response were obtained from the Ministry of Health. Data, for the period January 1 - March 9, 2014, reported salaries for people involved with the measles outbreak management medical team. The costs were reported as direct, additional (above normal budgeting) costs required to enable the management of measles. It includes a breakdown by individual performing the work and whether it was during the normal work schedule (Monday to Friday, M-F) or weekends. Normal work was calculated as $1.2 \times$ full time equivalent (FTE) $\times$ number of days worked. Overtime was calculated as $1.6 \times$ FTE (M-F) and $2.0 \times$ FTE (weekend). A full day was considered as 8 hours worked. Salary (hourly) rates were calculated for the following: public health nurse (PHN, \$36), public health assistant (PHA, \$22), data support (\$26), data support (temporary) (\$33), management and programme supervisors (\$40), incident management team (IMT), which had the following work titles: incident controller (\$96), administrator (\$24), planning and intel (\$40), logistics (\$36), communications (\$45), informatics (\$40), operations (\$40), and safety/security officer (SSO) (\$26). In addition, measles operations personnel were calculated at a daily rate of \$600 and operations partners and IMT controller partners at \$729.

Mean wages for New Zealand workers, by age and gender were obtained for the period, 2008–2013 from the New Zealand Income Survey (Statistics New

Table 12: Estimated costs (NZ$) for measles management in New Zealand, January 1 – March 9, 2014 (see text for abbreviations)

Category	January	February	March	Total
PHN	55,296	71,175	24,087	150,558
PHA	0	0	2,656	2,656
Data support	0	7,752	4,552	12,304
Supervisors	10,656	10,464	3,232	24,352
IMT	32,918	28,624	7,156	68,698
SSO	0	2,746	1,186	3,932
Measles operations	1,800	10,326	6,678	18,804
Operations partner	2,187	14,580	7,290	24,057
IMT controller partner	2,916	14,580	7,290	24,786
Total	105,773	160,247	64,127	330,147

Zealand, 2013). Measles cases were assumed to not work for a period of 5 days. Similarly, a care taker was assumed to not work for 5 days if the case were less than 20 years of age. In order to calculate the wage loss associated with the care taker, it was assumed that the person was a female between the ages of 35-39. Age and gender information for the 192 publicly funded hospital discharges with a measles primary diagnosis from 2008–2013 were matched to the New Zealand wage file to calculate lost wages due to measles.

A regression analysis was performed to test for significant associations between hospital cost and the following explanatory variables: case age at discharge, gender, length of stay (days) and year of case.

7.2 Cost analyses results

Direct costs for measles management in New Zealand for the 10-week period, January 1 – March 9, 2014 are shown in Table 12. The reported direct medical costs do not appear to include hospital medical costs, which are reported separately in Table 13.

The total cost for the 293 publicly funded hospital discharges with a measles primary diagnosis that spent 470 nights in hospital was $550,024 (Table 13). The mean cost per case was $1,877. The mean cost per day of stay in the hospital was $1,170.

From 16 December, 2013 through 19 June, 2014 there were 201 confirmed measles cases in New Zealand (note 14 of these occurred before 1 January 2014, so 187 occurred from Jan 2013 – 19 June 2014). The number of cases by age group is shown in Table 14. Of these 201 cases, 34 (17%) were admitted to hospital with the highest proportion occurring in the youngest (< 15 months) and oldest (> 19 years) age groups, 47% and 33%, respectively.

The length of hospital stay for the 293 cases reported between 2000 and 2014

Table 13: Number of cases, length of hospital day, cost, cost per case and cost per day for patients with measles as the primary diagnosis, 2000–2014

Year	Cases	Days	Cost	Per.case	Per.day
2000	6	13	8,850	1,475	681
2001	13	18	11,267	867	626
2002	5	2	3,869	774	1,934
2003	9	12	10,241	1,138	853
2004	4	5	4,765	1,191	953
2005	3	11	5,111	1,704	465
2006	1	0	602	602	NC
2007	5	25	82,977	16,595	3,319
2008	3	1	3,038	1,013	3,038
2009	29	38	40,782	1,406	1,073
2010	5	5	6,701	1,340	1,340
2011	132	189	205,303	1,555	1,086
2012	19	12	28,540	1,502	2,378
2013	4	6	5,330	1,333	888
2014	55	133	132,648	2,412	997
TOTAL	293	470	550,024	1,877	1,170

As of 11 July, 2014. NC - not calculated.

Table 14: Frequency of measles cases and number and proportion admitted to hospital by age group, 16 December, 2013 – 19 June, 2014

Age	Cases	Admitted	Proportion
<15 months	21	10	0.47
15 months – 3 years	7	1	0.14
4 – 9 years	8	0	0.00
10 – 19 years	132	12	0.09
>19 years	33	11	0.33
Total	201	34	0.17

ranged from 0 to 19 days, with a male patient, who was discharged in 2011 at age 57, after a stay of 19 days and a cost of $8,213 (Figure 27).

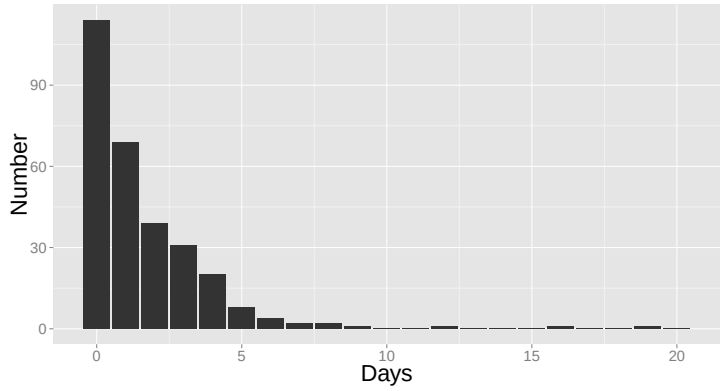

Figure 27: Number of measles cases attending hospital and stay duration from 2000–2014

Nearly 40% (114/293) of the cases did not spend a night in the hospital, while approximately one-quarter (69/293) spent 1 night and more than three-quarters (222/293) spent less than three nights in the hospital. Only eight cases spent a week or more in the hospital. Due to the small number of cases spending a week or more in the hospital, the regression analysis to determine the association between cost of hospitalisation was limited to the 285 cases hospitalised for seven or fewer days. The number of cases, length of hospital stay, cost, cost per case and cost per day for patients with measles as the primary diagnosis, by year and gender for 2000–2014 appear in Table 15.

Regression analyses showed statistically significant associations between cost of hospitalisation and three variables, length of hospitalisation, case age and year of case, and a less strong association with case gender (Table 16). Results showed the expected hospitalisation costs in 2000 of a female measles patient who did not stay overnight in the hospital was $582. The cost was $256 less if the case were a male. It increased of approximately $406 per night of hospitalisation and $64 per year over the time period of 2000–2014. The cost of a case decreased with the age of the patient by approximately $8 per year of case age.

Wages lost due to measles were calculated for the period January 2008 – August 2014. Calculations were based on the assumption that 5 days of work were lost for each case; however, individuals under 15 years of age were not assumed to be employed and therefore did not suffer an income loss. If the case were less than 20 years of age, it was assumed there was an income loss of 5 days for the care giver, in addition to the wage loss of the case if 15–19 years of age. Total wage lost for the 247 cases and care givers was estimated to be $210,436. This consisted of $107,820 for the cases and $102,616 for the care giver, but did not include wage losses for cases under 15 years of age. Overall, the cost per

Table 15: Number of cases, length of hospital stay, cost, cost per case and cost per day for patients with measles as the primary diagnosis, by year and gender, 2000–2014

Year	Gender	Cost	Cases	Length.of.stay	Cost.per.case
2000	F	4,296	2	4	2,148
	M	4,554	4	9	1,139
	Total	8,850	6	13	1,475
2001	F	3,740	5	5	748
	M	7,527	8	13	941
	Total	11,267	13	18	867
2002	F	924	2	0	462
	M	2,945	3	2	982
	Total	3,869	5	2	774
2003	F	9,766	8	12	1,221
	M	475	1	0	475
	Total	10,241	9	12	1,138
2004	F	1,437	1	2	1,437
	M	3,328	3	3	1,109
	Total	4,765	4	5	1,191
2005	F	0	0	0	0
	M	5,111	3	11	1,704
	Total	5,111	3	11	1,704
2006	F	0	0	0	0
	M	602	1	0	602
	Total	602	1	0	602
2007	F	1,930	1	3	1,930
	M	81,046	4	22	20,262
	Total	82,977	5	25	16,595
2008	F	714	1	0	714
	M	2,324	2	1	1,162
	Total	3,038	3	1	1,013
2009	F	11,953	7	15	1,708
	M	28,830	22	23	1,310
	Total	40,782	29	38	1,406
2010	F	5,884	4	5	1,471
	M	817	1	0	817
	Total	6,701	5	5	1,340
2011	F	103,460	66	86	1,568
	M	101,842	66	103	1,543
	Total	205,303	132	189	1,555
2012	F	13,054	8	6	1,632
	M	15,486	11	6	1,408
	Total	28,540	19	12	1,502
2013	F	1,800	1	2	1,800
	M	3,530	3	4	1,177
	Total	5,330	4	6	1,333
2014	F	55,633	21	46	2,649
	M	77,014	34	87	2,265
	Total	132,647	55	133	2,412
2000-2014	F	335,431	166	284	2,021
	M	214,591	127	186	1,690
	TOTAL	550,022	293	470	1,877

As of 7 August, 2014.

Table 16: Regression results ($R^2_{\text{adj}} = 0.43$, p-value < 0.001) for measles hospitalisation cost based on length of stay (days), gender, case age and year of case ($n = 288$) in New Zealand, 2000 – 2014

Variable	Coefficient	P.value
Intercept	581.39	<0.001
Length of stay (nights)	406.07	<0.001
Gender (0 = F, 1 = M)	−255.98	0.006
Case age (years)	−8.23	0.007
Year of case (vs. 2000)	64.35	<0.001

case from 2008–2014 was estimated to be ,327 ($852 in forgone wages, $1,765 in management costs, and $1,710 in hospital costs).

This final figure brings an approximate estimate of $809,149 for 187 cases for the current 2014 outbreak, which is comprised of earnings lost, case management and hospitalisation costs.

7.3 Benefit–cost analyses methods

To estimate the benefits from additional vaccinations, as estimated from the above modelling section (Section 5), we did several things. Primarily, we simulated 1000 measles outbreaks using the estimated R_v distribution from (Section 5) in the estimated susceptible population of naive New Zealanders (Figure 15). We assumed recovery from infection led to immunity and thus constantly reduced the population size by the number recovered. We used these values of numbers of predicted cases and the cost figures above to estimate what the cost of not vaccinating additional populations would be. We also simulated what we might expect measles outbreaks to look like following introductions in the population, given that R_v would be one, though where our estimates for R_v are already < 1, we use this. We can therefore estimate the number of cases prevented, and the savings made from the additional vaccinations. We then use the costs of the catch up vaccination schemes, the costs of the expected measles-related costs due to constant introduction of measles despite increased population immunity, and the savings from reduced measles cases to work out the benefit–cost ratio ((B/C), where a B/C ratio > 1 means that the program benefits exceed their costs. A B/C value less than one suggests the costs are higher than the economic benefits. Lastly, benefits were assessed over a 10–year time period, using a discounting rate of 3% discount per year for the costs, as is common for healthcare discounting [19]:

$$present\ value = \sum future\ value_{_{yr}} * (1/(1 + discount\ rate)^{yr} \tag{3}$$

Where $_{yr}$ is the year 0 (current) through to 9 (ten years into the future).

Our estimates for the numbers of measles cases are highly variable: if R_v were greater than one, either the measles outbreak would take off and all the susceptible New Zealand population would become infected during the outbreak, or the epidemic it would stutter after a few infects and fail to cause a large epidemic due to stochasticity. We used the average of 1000 simulations to estimate the mean of these stochastic simulations for our benefit–cost analysis. However, these simulations assume a homogeneously mixed population and thus give large epidemic sizes once the epidemic gets beyond the initial stuttering infection chains and this assumption is discussed below. However, to address this, we not only use R_v values of 1 in simulation models to estimate predicted outbreak sizes, but we also compared our results to those using the mean number of measles cases seen in New Zealand per year since 1997. This was 220 cases per year.

The numbers of susceptible people to vaccinate in New Zealand, assuming a homogeneously mixed population and using the upper 95% confidence limits of our R_v estimates (Section 5) are shown in Figure 28.

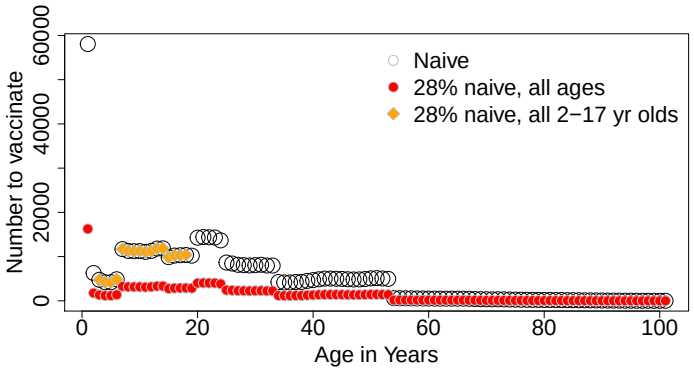

Figure 28: The estimated proportion of the currently naive New Zealand population requiring additional vaccination given alternative R_v values to reduce the R_v to one (Section 5, Tables **??** and **??**)

The expected number of cases in New Zealand, assuming homogenous mixing in a naive population of 11% of the population (the current status) and assuming measles R_v were 1 is shown in Figure 29 and Figure 30. These simulations show that even in scenarios when R_v is one, and thus stochastically should fail to persist (i.e. become endemic), large outbreaks can occur due to stochastic processes. Though the median value from 1000 simulations is low (2 cases), and thus most measles introductions will be single cases or lead to minor outbreaks, in this modelling exercise the mean value was 151 cases and the maximum nearly 25,000 cases.

For the cost analyses we used the values from the above cost section (Section 7.2). Specifically, we used the average cost of a case for the analyses to be

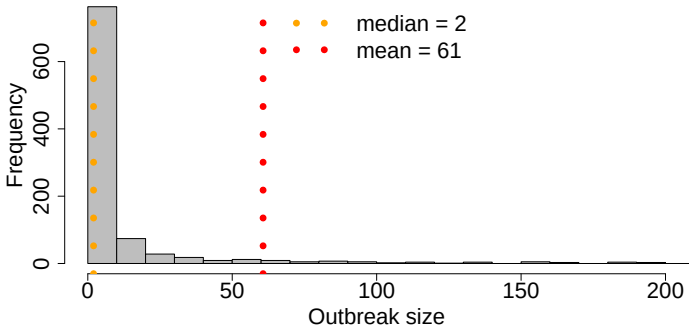

Figure 29: A subset of the expected number of measles cases from 1000 simulations of a model (Section 5) in a homogeneously mixed population in New Zealand with 11% susceptible to measles infection using an R_v =1. The full distribution of results can be seen in Figure 30

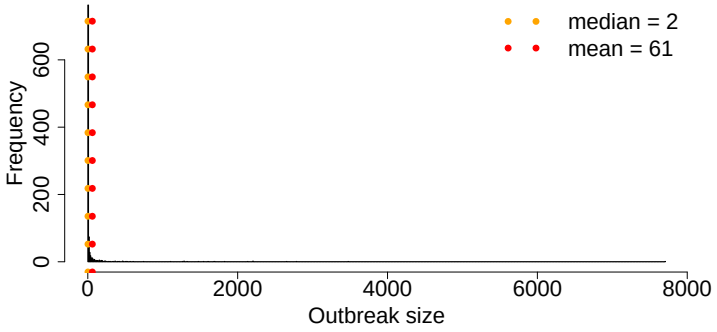

Figure 30: The distribution of the expected number of measles cases from 1000 simulations of a model (Section 5) in a homogeneously mixed population in New Zealand with 11% susceptible to measles infection using an R_v =1, showing the rare but possible large epidemic sizes possible. A subset of the distribution of results can be seen in Figure 29

$852 lost in wages and $1710 in hospitalisation costs for those attending hospital, with 17% of cases predicted to be hospitalised (Table 13). We estimated there would be approximately one introduction of measles per year (Section 4). We provide two costs for measles vaccinations for our cost analyses, $20 and $50, based on US literature.

7.4 Cost analysis discussion

The results presented here are based on available data. While some of the data are complete and detailed, this is not true of all the data. In order to perform an accurate analysis of the current measles outbreak in New Zealand, more complete data are needed. For instance, age, gender, ethnicity, year of discharge, length of stay and estimated cost data are available for cases reported by publicly funded hospitals. In addition to this information, similar data would be needed for cases occurring outside the period 2011–2013 at publicly funded hospitals. In addition, similar data would be needed for non-publicly funded hospitals, e.g. private clinics. Other factors that we aim to investigate are whether or not a linear term for case age is appropriate, or what if any interaction there might be between age and length of stay in hospital.

Detailed measles outbreak management costs were provided for the period of January 1 – March 9, 2014. Similar data are needed for the period preceding 2014. If detailed data, such as that provided for early 2014, are not available, aggregated data would be acceptable. However, it is unrealistic to assume that these costs would be linearly related with the number of measles cases, making it difficult to extrapolate these costs outside the reported period for 2014. As other studies have demonstrated, direct costs required to manage measles are not linear.

In other outbreaks, the average cost per measles case was estimated to be US$254, US$276, and US$307 for Canada, the Netherlands, and the UK, respectively (Carabin, et al., 2002). This and other findings will be compared and contrasted with New Zealand costs, once more complete New Zealand data are made available. The containment of a single case (also 2 secondary cases) of measles in 2004 in Iowa, USA was estimated to cost US$142,542. In this outbreak, more than 2500 hours of personnel time were needed to investigate and respond to the outbreak (Dayan et al., 2005). They estimated direct costs per case to be less than US$500. The annual cost for long-term care of people with moderate of severe mental retardation over a period of 50 years is estimated at US$31,059 and US$78,448, respectively [27]. In 2000 expenditures for care in large state mental retardation/developmental disabilities (MR/DD) facilities continued to increase and reached a national annual average of US$113,864 per person. In 2000 the average annual expenditures for care in large state MR/DD facilities were $113,864. The cost of a case of measles was estimated to range from $71 (no complications and no hospitalisation) to $29,556 (encephalitis and hospitalisation for 8.7 days). They estimated the annual cost of measles in the US with its vaccination program to be $1,234,083 (52.5% direct cost and 47.5% indirect cost) [40].

7.5 Benefit–cost analyses results

The benefit–cost results are in Table **??** and Table **??**. The results in the two tables show two alternative trends. In scenarios where we simulate the expected outbreaks in a homogeneously mixed population and R_v is above 1 the benefits of vaccination are always substantially greater than the costs of the increased supplementary vaccination (Table **??**). However, if the previous recent history of cases since 1997 is the *status quo* and what we may expect in the future then the *additional* effort to vaccinate the currently naive population of New Zealand based on R_v estimates that were greater than one is not a cost effective exercise (Table **??**).

It is worth noting that vaccination strategies that target the very young (<1 year old) may be less effective, as our analyses of the vaccinated cases suggests a substantial proportion of vaccinated cases that were vaccinated (Figure 22) were vaccinated with a single vaccine at a very young age (Figure 23).

7.6 Benefit–cost analysis discussion

The results presented here are based on available data, and only a 10 week period for the 2013–2014 outbreak. The majority of the cost analyses were discussed in our previous interim report and though some details have changed, we will focus here on the benefit–cost analyses. However, for all analyses more detailed costs of all aspects of hospitalisation would be beneficial. So too would information of the cost of measles vaccination in New Zealand.

We have used standard discounting from healthcare of 3% per annum [19], but again there may be official New Zealand discounting rates that we are unaware of. For our benefit–cost analyses we have not included measles outbreak management costs, though these were provided for the period of January 1 – March 9, 2014 (Table 12). Including these could be done, but we would like some further data of these before including them in our benefit–cost analyses. It is likely to be unrealistic to assume that these costs would be linearly related with the number of measles cases, making it difficult to extrapolate these costs outside the reported period for 2014.

In other nations' outbreaks, the average cost per measles case was estimated to be US$254, US$276, and US$307 for Canada, the Netherlands, and the UK, respectively [7]. In our analyses if we include loss of earnings and hospitalisation costs, our estimates are higher, around US$959 per case. This figure is from NZ$ 852 for loss of wages and 0.17 * NZ $ 1710 for costs related to attending hospital. However, costs can vary widely, with the containment of a single case and two secondary cases of measles in 2004 in Iowa, USA, estimated to cost US$142,542 alone [11].

Our estimates for the benefit–cost ratio of catch up vaccination are also much higher than those in some studies, if we presume the R_v is greater than 1 and measles will continue to circulate among the presently naive and susceptible New Zealand population until everyone has been infected. Estimates in Korea suggest catch up vaccination schemes have a benefit–cost ratio of just over one

Table 17: Cost benefit analyses with 20 dollars per vaccine

DHB	Vaccines	Vac.costs	Wage.loss	Management	Hospitalised	Hospitalisation	Costs	Outbreak	OB.costs	Benefit.cost
Auckland	17920	358400	26547468	55010965	5297	9057921	79616516	82	209524	140.19
Bay of Plenty	4585	91700	7188324	14895456	1434	2452636	21557962	71	181417	78.93
Canterbury	13687	273740	21040140	43598824	4198	7178837	63099902	62	158420	146.01
Capital and Coast	10461	209220	15679356	32490349	3129	5349752	47022778	96	245296	103.46
Counties Manukau	18880	377600	28033356	58089983	5594	9564902	84072731	50	127758	166.36
Hawke's Bay	3751	75020	5832792	12086558	1164	1990132	17492688	56	143089	80.20
Hutt Valley	4388	87760	6676272	13834395	1332	2277925	20022305	86	219745	65.11
Lakes	2886	57720	4423584	9166434	883	1509314	13266438	62	158420	61.38
MidCentral	4628	92560	7112496	14738327	1419	2426764	21330552	75	191638	75.06
Nelson Marlborough	2356	47120	3758172	7787585	750	1282278	11270851	90	229965	40.68
Northland	3071	61420	4846176	10042118	967	1653502	14533802	70	178862	60.49
South Canterbury	893	17860	1429656	2962496	285	487795	4287574	72	183972	21.24
Southern	8371	167420	12877980	26685411	2570	4393931	38621382	102	260627	90.23
Tairawhiti	1359	27180	2071212	4291911	413	706692	6211616	47	120093	42.18
Taranaki	2899	57980	4488486	9290019	895	1529663	13449923	68	173752	58.04
Waikato	11331	226620	17291792	35747682	3442	5886094	51772645	95	242741	110.30
Wairarapa	720	14400	1150830	2376352	229	391282	3442806	59	150755	20.85
Waitemata	17291	345820	26342544	54331250	5232	8946002	78740929	70	178862	150.07
West Coast	685	13700	1084105	2233347	215	367736	3237846	50	127758	22.89
Whanganui	1378	27560	2170740	4466695	430	735471	6477915	58	148200	36.86

Table 18: Cost benefit analyses with 50 dollars per vaccine

DHB	Vaccines	Vac.costs	Wage.loss	Management	Hospitalised	Hospitalisation	Costs	Outbreak	OB.costs	Benefit.cost
Auckland	17920	896000	26547468	55010965	5297	9057921	79616516	82	209524	72.02
Bay of Plenty	4585	229250	7188324	14895456	1434	2452636	21557962	71	181417	52.49
Canterbury	13687	684350	21040140	43598824	4198	7178837	63099902	62	158420	74.87
Capital and Coast	10461	523050	15679356	32490349	3129	5349752	47022778	96	245296	61.20
Counties Manukau	18880	944000	28033356	58089983	5594	9564902	84072731	50	127758	78.44
Hawke's Bay	3751	187550	5832792	12086558	1164	1990132	17492688	56	143089	52.91
Hutt Valley	4388	219400	6676272	13834395	1332	2277925	20022305	86	219745	45.59
Lakes	2886	144300	4423584	9166434	883	1509314	13266438	62	158420	43.82
MidCentral	4628	231400	7112496	14738327	1419	2426764	21330552	75	191638	50.42
Nelson Marlborough	2356	117800	3758172	7787585	750	1282278	11270851	90	229965	32.41
Northland	3071	153550	4846176	10042118	967	1653502	14533802	70	178862	43.72
South Canterbury	893	44650	1429656	2962496	285	487795	4287574	72	183972	18.75
Southern	8371	418550	12877980	26685411	2570	4393931	38621382	102	260627	56.86
Tairawhiti	1359	67950	2071212	4291911	413	706692	6211616	47	120093	33.03
Taranaki	2899	144950	4488486	9290019	895	1529663	13449923	68	173752	42.20
Waikato	11331	566550	17291792	35747682	3442	5886094	51772645	95	242741	63.97
Wairarapa	720	36000	1150830	2376352	229	391282	3442806	59	150755	18.43
Waitemata	17291	864550	26342544	54331250	5232	8946002	78740929	70	178862	75.46
West Coast	685	34250	1084105	2233347	215	367736	3237846	50	127758	19.99
Whanganui	1378	68900	2170740	4466695	430	735471	6477915	58	148200	29.84

[6]. However, if we presume that in a totally naive population R_0 for measles is around 12, and sometimes estimated to be more than 18 (i.e. 1 case infects 18 others on average, [2]) then the majority of naive people becoming infected is not unrealistic given some of our R_v estimates (Figure 26). The benefits of catch up vaccination are clear once R_v is greater than one (Table **??**). If measles continues to cause smaller outbreaks, and/or R_v is less than one (Figure 26), then there is little financial benefit in additional vaccination (Table **??** and Table **??**), though there may be medical and other benefits relating to maintaining measles free status that we have not included in our report.

Finally, our model of measles introductions is a simple one, and more complex models may predict smaller outbreaks depending on contact structure and other scenarios, such as the size of the local naive population. The spatial effects of measles transmission may have affected both our multivariate regression analyses (Section 4) and will affect the predictions from modelling exercises (Section 5). Whatever happens, however, it is clear that there will be ongoing costs to maintain New Zealand free of endemic measles and introductions occurring on an annual basis (see previous report) may produce some large and costly outbreaks, even if vaccination cover is high and R_v is less than one (Figure 29 and Figure 30).

7.7 Cost analysis summary

- Our initial estimates suggest the ongoing 2013–2014 measles outbreak has cost New Zealand over $750,000.

7.8 Benefit–cost analysis summary

- The mean wage losses per measles case is estimated to be $852
- The mean cost per measles case attending hospital is estimated to be $1710
- Approximately 17% of measles cases attend hospital
- For R_v values estimated for the 2013–2014 outbreak and the upper bounds estimated for all outbreaks since 2009, the benefits of catch up vaccination strategies are clear (>1 B/C ratio).
- For R_v values at the lower bounds of the estimates for all outbreaks since 2009, the benefits of catch up vaccination strategies are not clear and may not be cost effective (<1 B/C ratio).
- Large outbreaks, with a mean size of approximately 151 cases per year, median of 2, but peak size of up to many thousands, may occur regularly due to importation, despite R_v being below one and the epidemic predicted to die out without additional interventions.

7.9 Future cost-benefit analyses

Using the results above we aim to:

- Estimate the costs and benefits for targeted vaccination, based either on the univariate analyses presented to date in the *Progress Towards Measles Elimination in New Zealand - Final* report or adjusted if any additional risk groups are identified in the multivariate analyses (section 4) or modelling (section 5).

We also require additional clarifications of the data, regarding:

- What hospital costs refer to, such as if a hospital day were 0 does that mean the case stayed in the hospital but not overnight? Or, does it mean the case stayed for less than 24 hours?

Once more complete data are available, comparisons of these results will be made to other published studies, discussed above.

8 Summary of key findings

- New Zealand is at risk of frequent measles importation due to travel and endemic measles elsewhere in the world.
- The cost of the current measles outbreak is estimated to be at least $750,000.
- Analyses of outbreak data suggest that measles R_v values often include 1 and in this year, 2014, are well above one. This analysis suggests improved vaccination is a requisite to prevent measles becoming endemic again.
- Risk of measles infection decreases significantly with age
- Pacific people are statistically more at risk on a per capita basis, as are those living in better socio-economic situations
- Pacific and Asian children in the 6–17 year age categories have been at lower risk of measles than European or Maori children of the same age
- Additional vaccination levels to push R_v below one among the currently naive population in New Zealand range from 0% ($R_v < 1$) to 53% (R_v 2.13, upper 95% confidencelimit 2013–2014 outbreak, approximately 250,000 vaccinations), depending on the appropriate reproduction number, R_v, for measles in New Zealand.
- The mean wage losses per measles case is estimated to be $852
- The mean cost per measles case attending hospital is estimated to be $1710, and approximately 17% of measles cases attend hospital

- For R_v values estimated for the 2013–2014 outbreak and the upper bounds estimated for all outbreaks since 2009, the benefits of catch up vaccination strategies are clear (>1 B/C ratio).
- For R_v values at the lower bounds of the estimates for all outbreaks since 2009, the benefits of catch up vaccination strategies are not clear and may not be cost effective (<1 B/C ratio).
- Large outbreaks, with a mean size of approximately 151 cases per year, median of 2, but peak size of up to many thousands, may occur regularly due to importation, despite R_v being below one and the epidemic predicted to die out without additional interventions.

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