1. Introduction

Globally, it is well recognised that maternal immunisation prevents severe influenza morbidity in pregnancy and severe infant pertussis and influenza in the first weeks of life.[1-3] Recent studies have demonstrated that immunisation in pregnancy is highly effective against maternal and infant influenza and pertussis. Despite excellent safety profiles in pregnant women[4-7] and fully funded maternal influenza and pertussis immunisation in Aotearoa New Zealand (NZ), maternal vaccination coverage has remained suboptimal, with recent evidence suggesting inequities in coverage have increased over time.[8-11]

Despite strong evidence of efficacy and safety and the funding of pertussis and influenza vaccines for pregnant women in NZ, maternal vaccination coverage remains significantly lower than optimal levels.[12] In a recent examination of maternal vaccine coverage at the national level, Māori (who are the indigenous people of NZ) and Pacific women were significantly less likely to have received pertussis vaccine (Māori OR=0.55 [95% CI: 0.54, 0.57]; Pacific OR=0.60 [0.58, 0.62]) and for Māori women influenza vaccine (OR=0.69 [0.67, 0.71]) compared to NZ European or 'Other' women.[12] Māori babies currently make up 26% of all births; addressing inequities in maternal immunisation requires urgent action.[13]

While differences in maternal coverage related to deprivation and ethnicity have been well documented in high-income countries[14,15] few studies have examined clustering of low immunisation coverage areas over space and time[16-17]. For instance, it may be that in some localised patterns of immunisation coverage with clusters of areas in NZ where low levels of immunisation cluster together and these low levels of immunisation may also be persistent over time. Childhood immunisation coverage in NZ has declined recently, exaggerated by the COVID-19 pandemic.[16-17] A spatio-temporal analysis from 2005 to 2017 in NZ identified clustering of low childhood immunisation coverage in more densely populated areas[16-17], similar to subsequent patterns of uptake of COVID-19 vaccines.[18] This study examined geo-spatial variation to identify persistent hot (high coverage) and cold (low coverage) spots and trends in immunisation coverage by region, aimed at highlighting areas for intervention.

2. Methods

2.1 Study design

This was a retrospective geospatial cohort study. The study population included all pregnant women[i] with a delivery between 01 January 2013 and 31 December 2020. In line with previous practice[8], women were excluded if the gestational age at delivery was less than 20 weeks or greater than 45 weeks (most women are induced at 43 weeks or earlier), were missing date of last menstrual period or a gestational age at delivery, if maternal age at delivery was less than 12 years of age or greater than 50 years of age, identified as non-resident, or were not enrolled for primary health care delivery.

2.2 Data

Sources of administrative health data in NZ for this study are the National Maternity Collection, National Health Index, Primary Health Organisation enrolments, National Immunisation Register, Proclaims, and the Pharmaceutical collection. Please see supplementary text for detail.

2.3 Outcomes

Our study had two key outcomes of interest: receipt of influenza or pertussis vaccine during pregnancy. Vaccination status was defined as a binary outcome for each woman who had a valid entry for a pertussis vaccine and/or influenza vaccine in any data source during their eligible pregnancy period. In line with previous research[8], due to the number of data sources available with vaccination information, they were prioritised in the following order: NIR, Proclaims, and Pharmaceutical Collection. Multiple

[i] we use the term woman/women but acknowledge the gender diversity of birthing people in Aotearoa New Zealand

vaccinations events could have been reported - only the first valid entry was selected. A vaccine record was considered valid if it occurred between the last menstrual period and delivery date.

Geographic information was obtained from primary health enrolment data matched to the time period of the pregnancy, with meshblock data used to identify residence at Territorial Authority (TA) level. TAs form the second tier of local government in NZ, below regional councils which comprise 67 city and regional councils. Additionally, District Health Boards (DHB), which were the model for funding and providing health services in NZ until 2022 with 20 regions[20] were examined.

2.4 Analyses

Firstly, immunisation coverage was mapped at TA and DHB level for: 1) overall rates (%) based on pooled data (2013–2020) and 2) annually in individual years. Then we focused on the identification of spatio-temporal patterns using Emerging Hot Spot Analysis (EHSA).[19] The aim of the analysis is to identify clusters of areas (or points) that share similar patterns in their characteristic(s) both spatially and in their temporal trends. It combines a spatial hot spot analysis (Getis-Ord Gi*) exploring spatial autocorrelation in the data with Mann-Kendall test for monotonic trends.[21] To use EHSA, data needs to be transformed to a space-time cube, which is an object containing spatial (location) and data reference (immunisation rates) organised in the regular structure with the vertical dimension representing time. The inference is based on the analysis comparing patterns within a selected spatial neighbourhood and time lags in the neighbourhood. The queen contiguity-based spatial weights with a time lag $k = 1$ was used in the settings of the analysis. This means we were evaluating neighbours sharing a border (TA) and their rates within two consequent steps. The significance threshold of EHSA was set as 0.01 after 199 simulations.[21]

EHSA can detect up to 17 possible spatio-temporal patterns characterised as either: no pattern, cold-spot or hot-spot that are further categorised for temporal trends as new, consecutive, intensifying, persistent, diminishing, sporadic, oscillating or historical.[19] Here we provide only a description of patterns identified within the immunisation coverage data based on: 1) *no pattern detected* - no spatio-temporal pattern within the selected significance threshold; 2) *new hot/cold spot* - a statistically significant hot/cold spot of immunisation coverage for the final time step (never been a statistically significant hot/cold spot before); 3) *consecutive hot/cold spot* - a statistically significant hot/cold spot bins in the final time-step intervals (never been a statistically significant hot/cold spot prior and less than ninety percent of all bins are statistically significant hot/cold spots); 4) *sporadic hot/cold spot* - a location that is an on-again then off-again. Less than ninety percent of the time-step intervals include statistically significant hot/cold spots and none of the time-step intervals have been statistically significant cold/hot spots; 5) *oscillating hot/cold spot* - a statistically significant hot/cold spot for the final time-step interval that has a history of also being a statistically significant cold/hot spot during a prior time step. Less than ninety percent of the time-step intervals have been statistically significant hot/cold spots.[19] Table 1 then provides a further visual description of categories identified within the analysed dataset. R was used for both analysis and visualisation of results.[23] The code and data are available at https://github.com/lukysmarek/mamahapu.

Table 1. Classification of spatiotemporal patterns identified in the vaccination data and their visual representation.

Cluster type	**Time step** -2	**Time step** -1	**Time step** Final	**Pattern description**
No pattern				No spatio-temporal pattern detected within the selected significance threshold
New hot spot				A statistically significant hot/cold spot of immunisation coverage for the final time step and never been a statistically significant hot/cold spot before
New cold spot				
Consecutive hot spot				A statistically significant hot/cold spot in the final two time-steps, never been a statistically significant hot/cold spot prior
Consecutive cold spot				
Sporadic hot spot				A location that is repeatedly on and off
Sporadic cold spot				
Oscillating hot spot				A statistically significant hot/cold spot for the final time step that has a history of also being a statistically significant opposite cluster during a prior time step
Oscillating cold spot				

3. Results

3.1 Descriptive statistics

Our cohort of 367,475 pregnant women had 429,985 pregnancies between 2013 and 2020, of which 26.5% were to women who identified as Māori and 9.7% were to Pacific women. Table 2 provides further detailed view of pregnant women and their vaccination status.

Table 2. New Zealand pregnant women who birthed between 1 January 2013 and 31 December 2020, by vaccination status.

	Total		Pertussis Vaccinated		Influenza Vaccinated	
	n	%	n	%	n	%
Delivery Year						
2013	54,380	(12.7)	5,550	(10.2)	6,115	(11.2)
2014	54,650	(12.7)	8,647	(15.8)	9,628	(17.6)
2015	54,242	(12.6)	11,127	(20.5)	10,613	(19.6)
2016	54,436	(12.7)	15,744	(28.9)	12,944	(23.8)
2017	53,941	(12.5)	19,460	(36.1)	15,001	(27.8)
2018	51,973	(12.1)	22,702	(43.7)	16,042	(30.9)
2019	54,149	(12.6)	24,704	(45.6)	18,470	(34.1)
2020	52,214	(12.1)	25,035	(48.0)	22,738	(43.6)
Prioritised Ethnicity						
Māori	113,999	(26.5)	18,509	(16.2)	18,330	(16.1)
Pacific	41,749	(9.7)	8,482	(20.3)	9,111	(21.8)
Asian	62,906	(14.6)	27,601	(43.9)	23,962	(38.1)
Other	8,894	(2.1)	3,082	(34.7)	2,632	(29.6)
New Zealand European	202,434	(47.1)	75,294	(37.2)	57,515	(28.4)

3.2 Spatial and spatio-temporal immunisation coverage

Figure 1 shows a print screen of the interactive dashboard that allows users to browse and interact with the data about maternal immunisation coverage available at: https://geohealthlab.shinyapps.io/hapumama/. Overall, it is important to highlight that immunisation coverage is suboptimal. Even in district health boards (DHB) with relatively higher rates of immunisation coverage, this is only around 50% of mothers which means that half of the women who are pregnant (183,737 women) are not protected. Maps of immunisation rates of influenza and pertussis by Territorial Authorities (TAs) are available between 2013 and 2020 either as overall rates or by ethnicity. Additionally, there are two graphs displayed on the interactive dashboard. One graph provides annual immunisation rates (overall or by ethnicity) by TAs, while the other graph displays a change in immunisation rates over time in selected TAs with comparison of overall rates with ethnicity-specific immunisation rates in the area.

Figure 2 shows the overall level of maternal immunisation coverage for influenza and pertussis from 2013 to 2020 by DHB, the entities responsible for distribution of funding most health care in their regions. There were clear differences and large spatial variation in immunisation coverage for both influenza and pertussis. For instance, DHBs such as Canterbury, Auckland and Capital & Coast had relatively higher levels of immunisation coverage relative to other DHBs including, but not limited to, Tairāwhiti, Waikato, Northland, Bay of Plenty, West Coast and Taranaki. These pooled data from 2013 to 2020 highlight the significant inequities in maternal immunisation coverage by DHBs.

Figure 3 highlights at a finer geographical scale the annual level of maternal immunisation coverage for Influenza from 2013 to 2020 by TA. While the data in Figure 2 are useful for ranking DHB coverage, Figure 3 provides more depth to show variation by smaller area geography, territorial authority. These data are also available to explore in the interactive shiny app but highlight important within DHB variation in coverage. Figure 4 demonstrates the annual level of maternal immunisation coverage for Pertussis from 2013–2020 by TA. Again, these data are available to interactively explore in the shiny app however, coverage is generally higher in urban authorities.

Figure 5 presents the findings of an emerging hotspot analysis of maternal influenza immunisation rates from 2013 to 2020 by ethnicity in the TAs. As outlined previously in the methods, hot-spots have higher than expected coverage relative to their neighbouring areas whereas cold-spots have lower than expected coverage relative to their neighbouring areas. Findings overall show the presence of sporadic and oscillating cold spots that denote TAs with rather low immunisation rates when compared to their neighbouring areas. However, there is also a visible trend of new and consecutive hot spots throughout the country, which means there are numerous improvements visible even in the areas of low coverage. By ethnicity, one can see improvements in Māori maternal immunisation coverage, especially in the area around Hamilton (Waikato), Tairāwhiti, central North Island and some of South Island's TAs. In general, the Asian population is the one with the highest and growing immunisation coverage while Europeans show the least improvement represented by a presence of cold spots of all types throughout the country.

Finally, Figure 6 shows the findings of another emerging hotspot analysis of maternal pertussis immunisation rates from 2013 to 2020 by ethnicity in the TAs. Overall, our findings show improvements in maternal pertussis immunisation represented by a number of hot spots (especially consecutive). However, there is also a high number of sporadic cold spots, particularly in the central North Island and rural areas of the South Island except Southland and Marlborough. While Māori and Pasifika have lower immunisation rates than Asian or European mothers, their spatio-temporal pattern shows constant improvement.

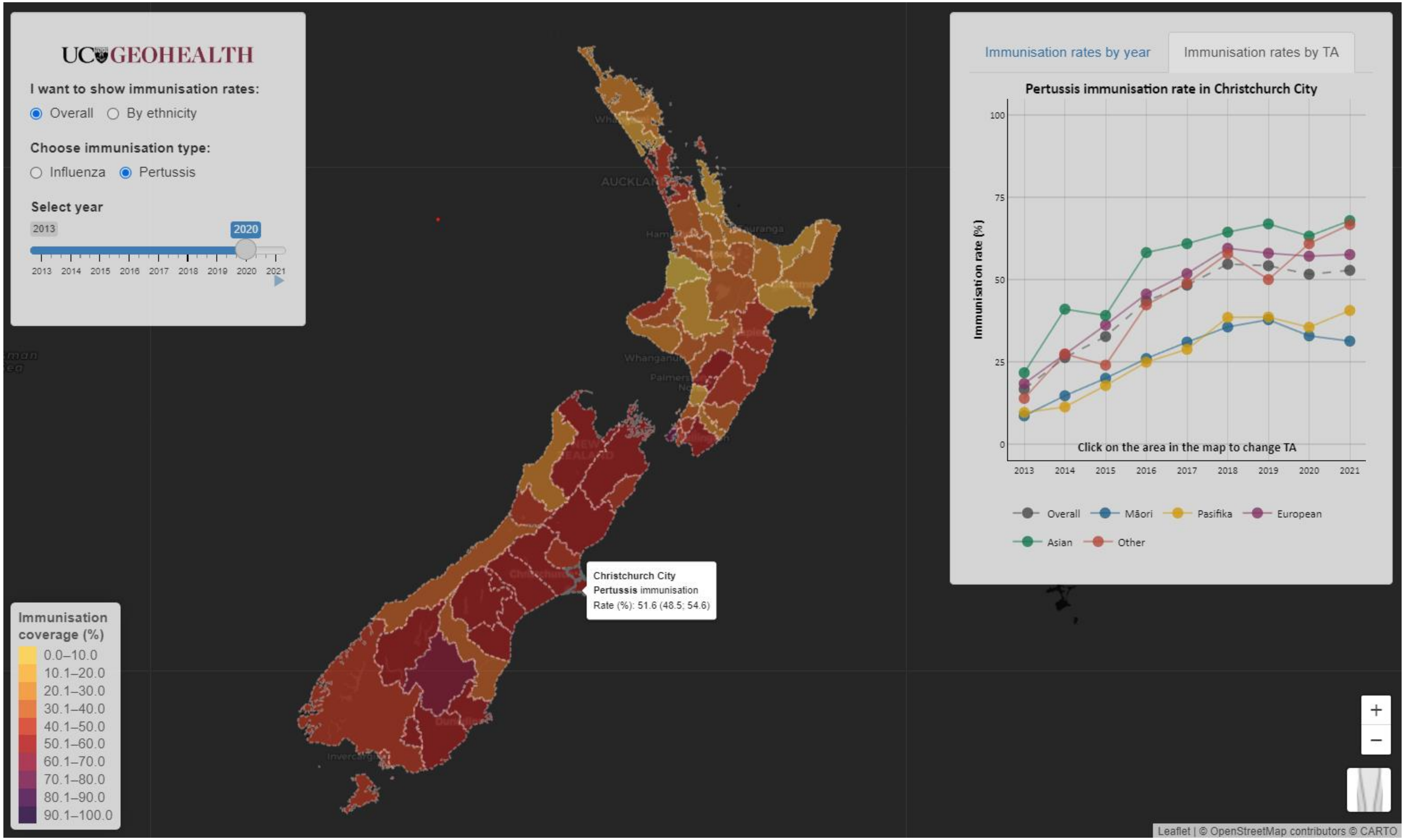

Figure 1. Shiny app example and link (condition, by year)

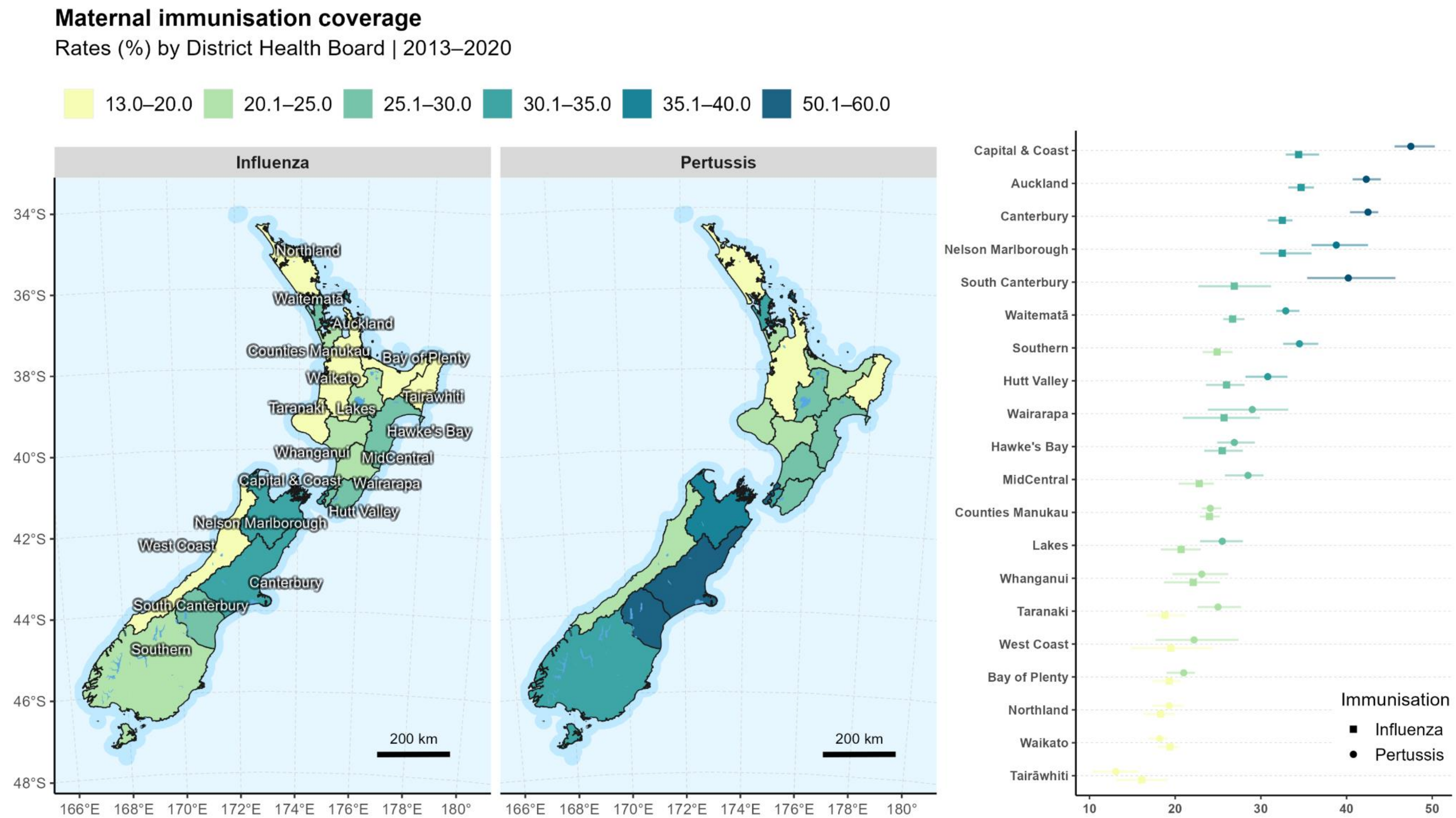

Figure 2. Overall level of maternal immunisation coverage for Influenza and Pertussis from 2013–2020 by District Health Board.

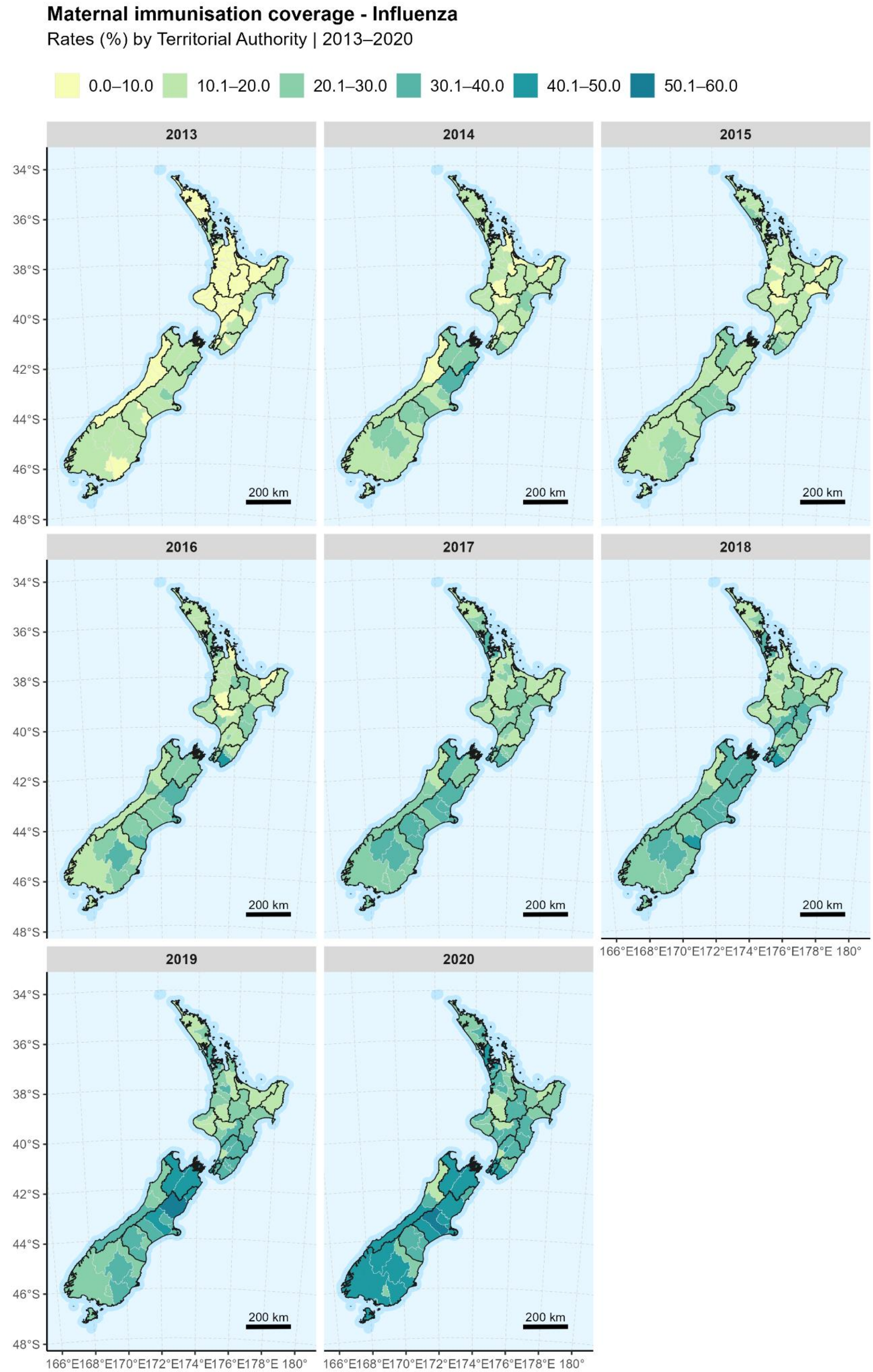

Figure 3. Annual level of maternal immunisation coverage for Influenza from 2013–2020 by Territorial Authority (black lines represent DHB boundaries).

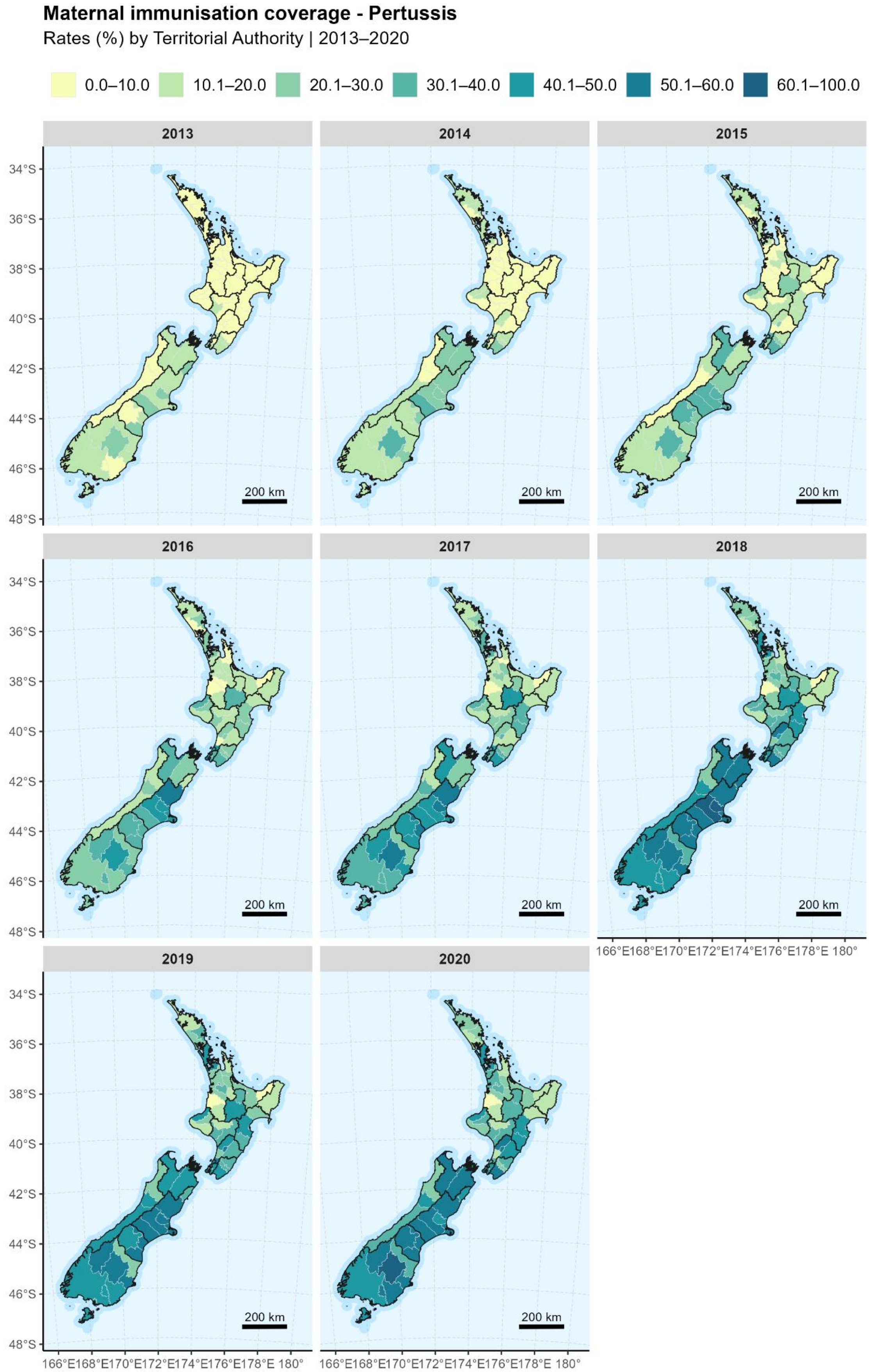

Figure 4. Annual level of maternal immunisation coverage for Pertussis from 2013–2020 by Territorial Authority (black lines represent DHB boundaries).

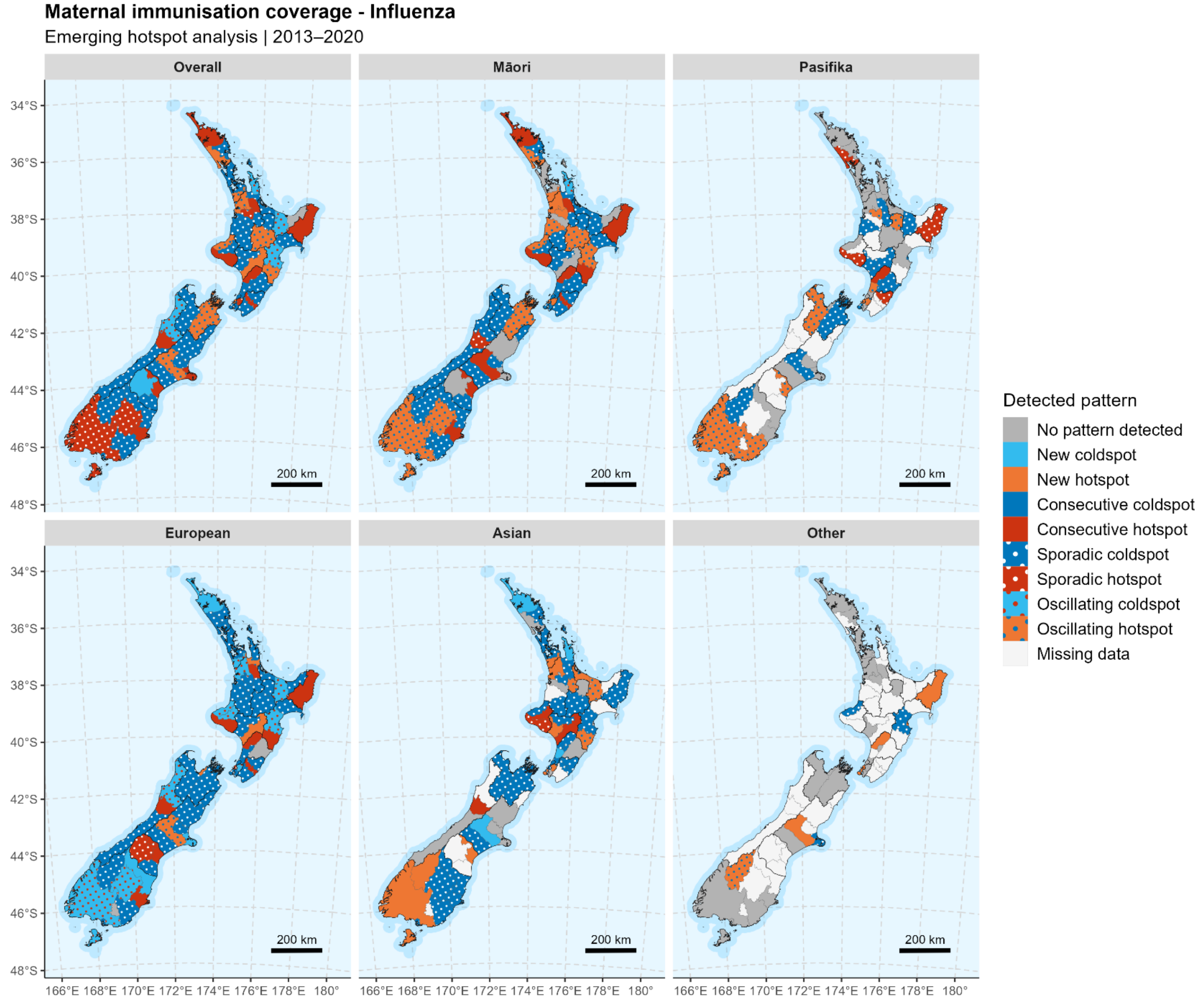

Figure 5. Emerging hotspot analysis of maternal influenza immunisation rates from 2013–2020 by Territorial Authority (black lines represent DHB boundaries).

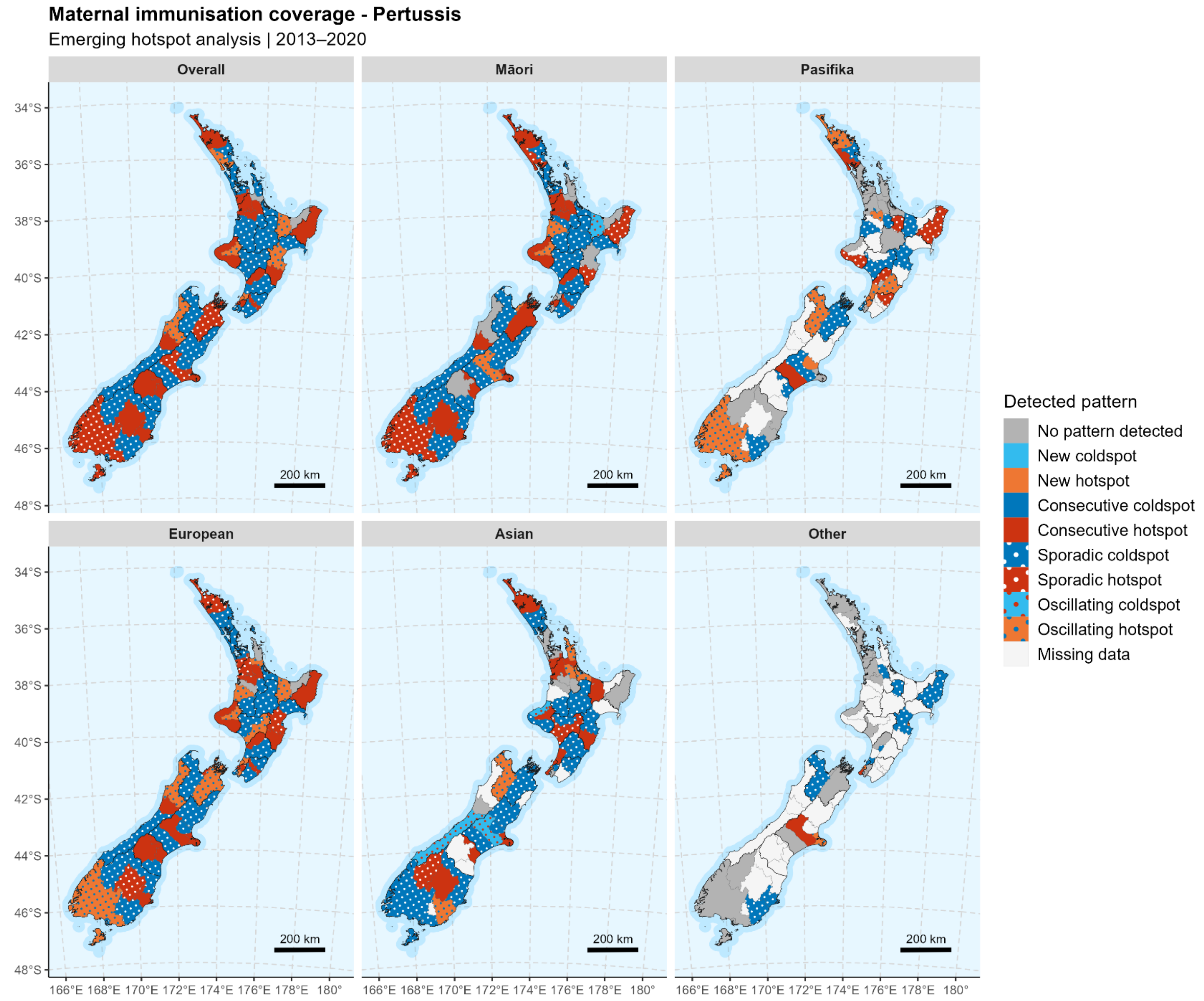

Figure 6. Emerging hotspot analysis of maternal pertussis immunisation rates from 2013–2020 by Territorial Authority (black lines represent DHB boundaries).

4. Discussion

This retrospective cohort study examined nationwide spatial variation in maternal immunisation coverage across NZ from 2013 to 2020. Our findings show that immunisation coverage is suboptimal but even in district health boards (DHB) with higher rates of immunisation coverage this is only around 50% of mothers, meaning that half of the women who are pregnant (183,737 women) are not protected. Internationally, immunisation during pregnancy is highly effective against maternal and infant influenza and pertussis. However, most international literature to date has not provided a spatio-temporal examination of immunisation coverage. In addition, it seldom can provide an investigation at a nationwide scale using small geographical areas to display coverage. This is the kind of information that can be utilised by policy makers or to inform interventions, to reduce health inequity.

Our study used data on 429,985 pregnancies and found that while coverage increased from 2013 to 2020 there was significant spatial variation in the extent to which the increase took place. Our study also extended international evidence by accounting for spatio-temporal changes in immunisation coverage to detect for instance, where new clusters of high coverage may be emerging or where coverage may be decreasing over time. Importantly, we add to evidential rigour by using a range of data sources to gain an accurate depiction of maternal immunisation coverage. To the authors' knowledge, this study provides one of the first nationwide investigations to demonstrate significant spatio-temporal variation in maternal immunisation coverage which will have important implications for shaping policy and intervention. Our findings are available to interactively explore here: https://geohealthlab.shinyapps.io/hapumama/.

Antenatal immunisations are critical to protect mothers against influenza during pregnancy and pertussis in the first weeks of the infant's life. Our study supports these concerns with findings indicating significant spatial variation in maternal immunisation levels by DHB. DHBs are the funding bodies for most health in their region. To complicate matters, maternity care funding is a mixture of central and regionally funded. However, the discretion DHBs have with funding has resulted in the focus on maternal immunisation and the mechanisms that they employ to provide immunisation services varying regionally. For example, our study shows increases in maternal coverage in the Waikato DHB over time, which has been funding pertussis immunisation for pregnant women in community pharmacy since 2016. Previous work has been shown this to increase uptake, particularly for Māori women.[12] This broadly supports a previous nationwide study which highlighted similar areas of the low coverage for childhood immunisation.[16,17] Identifying and addressing procedural gaps in local populations is critical to influence acceptance and uptake and make positive change.[24]

In our nationwide study, while DHB coverage was variable, analyses at a finer geographical scale by smaller areas (TAs) revealed within-DHB variation. Several TAs were defined as hot-spots, which have higher than expected coverage relative to their neighbouring TAs, as well as cold-spots, which have lower than expected coverage relative to their neighbouring TAs. For instance, in Northland DHB, which previous evidence has shown low immunisation coverage,[16,17] we identified several TAs as consecutive hot-spots, particularly for Māori, for both influenza and pertussis. In contrast, other TAs within Northland DHB are classified as a sporadic cold-spot. This highlights variation at a much finer geographical scale in coverage which to our knowledge, has seldom been explored internationally. Second, our TA hot-spots and cold-spots often cross DHB boundaries which suggests more locally nuanced or community-level factors influencing coverage. We add to evidence, which has previously shown differences in vaccine uptake in Australia between First Nations and non-First Nations women for both influenza and pertussis vaccines − 31% and 42% for influenza; 55% and 69% for pertussis, respectively.[14] Our study also supports several other articles which have confirmed spatial variation in measles coverage with persistent low areas[25] and spatial variation in COVID-19 coverage.[26]

Poor maternal immunisation coverage is a complex problem affecting many countries around the world, with no single solution.[27] Thus, improving coverage across the country will require a multipronged approach, with interventions at the structural, social, and behavioural level.[27,28] Being informed about immunisation by a trusted healthcare provider, e.g. a GP or midwife, improves willingness to be vaccinated.[29] However, barriers to accessing healthcare services may be a significant concern for some people who seek immunisation. For instance, some women have difficulty in accessing a midwife and/or GP services.[30,31] Access to immunisations in NZ came to the fore in 2021 during the COVID-19 pandemic, sparking a nationwide campaign to promote vaccination with messaging on various platforms including social media, television, radio, and printed media.[32] Unfortunately, no such campaign on this scale has been implemented for maternal vaccination. Access has partially been addressed with pharmacies across NZ providing funded maternal influenza vaccination since 2017 and pertussis since September 2022, which we know increases uptake.[8,12] Despite this, we know that health services are inequitably distributed.[33,34] Midwife-led vaccination services have also been shown to be effective,[2, 22] and there are midwives in NZ approved to vaccinate against influenza and pertussis. Having midwives and pharmacists providing immunisation services offers the additional benefit of enabling recommendations from an accessible and trusted healthcare professional, which greatly increases the likelihood of choosing to be immunised,[29] to be followed up at a convenient time and location for immunisation.

The rigour of this study is strengthened by the use of multiple data sources to depict maternal immunisation coverage as well as by using a novel geospatial lens which is seldom considered in this area of research. However, it also has a number of limitations. First, due to the granularity of the data we were unable to show maternal vaccination coverage at a finer geographical scale which does not make comparisons based on deprivation and accessibility feasible. For instance, future work would benefit from investigating coverage at a finer geographical scale such as Statistical Area 1 (SA1) however, we were unable to go smaller in this study due to potential identification/confidentiality issues. Second, influenza vaccinations delivered in workplaces are not usually captured by governmental claims data or registered in the National Immunisation Register. Consequently, it is possible pregnant women who received their influenza vaccination through an occupational scheme have not been included in this study and therefore maternal influenza coverage may have been underestimated.[8] Third, our study did not investigate or analyse what the associations between different enablers and barriers to maternal vaccination were, such as health-seeking or health practitioner behaviours. While it is not possible to capture the influences on maternal vaccination within our study these are important considerations for future research to investigate. Fourth, as the emerging hot spot analysis evaluates spatio-temporal trends and patterns only within the closest area, it is not suitable for a direct comparison of the absolute rates nationwide but rather serves as an opportunity to directly compare local trends possibly pointing out to differences in the local governance.

5. Conclusion

This retrospective cohort study is, to our knowledge, one of the first to investigate spatial variation in maternal vaccination coverage in pregnant women over an extended period allowing for a nuanced assessment of changes in regional coverage. Our nationwide and geospatial analyses offer some hope by demonstrating an upward trend in some areas of NZ however, inequities are still apparent in many areas. The areas where there is poor immunisation coverage but also where there are some slow improvements, can inform future intervention and policy in maternal immunisation coverage, but could equally be applied to other areas of health policy. In NZ, our evidence is timely given the current health reforms underway with a move towards a national health service, the creation of Te Whatu Ora | Health NZ and Te Aka Whai Ora | Māori Health Authority. Our geospatial analyses approach has the potential to inform and thus minimise the inequitable regional differences in healthcare provision and maternal immunisation coverage, in NZ and other countries.

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Data Sharing Statement:
Routinely collective administrative data were used to undertake this study. All data collected for the study are currently availble from New Zealand's Ministry of Health Data Data Services Team (data-enquiries@health.govt.nz).