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Examining spatial variation and inequity in COVID-19 immunisation coverage in Aotearoa New Zealand: a nationwide geospatial study

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ABSTRACT

Background: Aotearoa New Zealand (NZ) was almost unique worldwide in having very limited community transmission of COVID-19 prior to March 2022. Using nationwide data, we examined variation in COVID-19 immunisation coverage in adults in 2022, when NZ transitioned from elimination to mitigation in a largely infection-naïve population.
Method: We used the COVID-19 Immunisation Register (CIR) within the Integrated Data Infrastructure (IDI) to calculate immunisation coverage among adults aged 18 years and over between 1st January and 31st December 2022 by age, ethnicity and residential address. Geospatial analyses were undertaken in ArcGIS Pro.
Results: Among adults >65 years, between January and March 2022, when widespread community transmission of COVID-19 began, uptake of third doses increased for European ethnicity by 7.9 %, reaching 87.0 % by December 2022 and by 18.5 % in Māori, 21.6 % in Pacific and 24.2 % in Asian people, reaching 80.7 %, 80.2 % and 83.5 % by December. In contrast, the proportion of adults >65 years of any ethnicity who had received zero doses by January 2022 remained stable from 6.3 % (Asian) to 10.8 % (Māori), with less than 0.15 % receiving any doses by December. Third dose uptake was lowest and zero doses highest in adults of all ages living in the most deprived and among Māori and Pacific people. Among Asian people, the proportion zero dose was highest >65 years, whereas in other ethnic groups it was highest in younger adults. There was significant spatial variation by area with a greater proportion of zero-dose populations in more rural areas.
Conclusion: Our study is among the first internationally to examine patterns of non-receipt of COVID-19 vaccines and differences in age-related coverage by sociodemographic factors which have implications for tailored communication and community engagement.

1. Introduction

Vaccination is one of the most effective public health interventions to prevent infectious diseases and reduce morbidity and mortality worldwide [1]. The development and deployment of COVID-19 vaccines represented an unprecedented global effort to control the SARS-CoV-2 pandemic, protect healthcare systems, and reduce the societal and economic impacts of widespread infection [1,2]. Indeed, vaccination against COVID-19 substantially reduced mortality in every global region especially for older adults [1]. Aotearoa New Zealand (NZ) implemented a world-leading COVID-19 elimination strategy in 2020 and 2021, resulting in almost all the population being vaccinated before being exposed to community transmission of COVID-19 [2], delivering one of the lowest pandemic mortality rates in the world [2].

The lack of community transmission before widespread infection following the opening of NZ's borders and the arrival of the Omicron

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variant meant that neither infection-related or hybrid immunity [3] was present in the population, allowing assessment of the impact of third dose (booster) coverage of COVID-19 vaccine as the almost exclusive factor in preventing severe morbidity and mortality in 2022. However, previous work had demonstrated disparities in COVID-19 immunisation coverage during vaccine rollout in NZ in 2021, with a dynamic interplay of disease burden, health disparities, and behavioural patterns [3], and inequities in immunisation coverage in underserved communities [4–6]. In countries experiencing sustained community transmission of COVID-19, the burden of infection and severe outcomes varied across geographic areas, often disproportionately affecting underserved populations [7]. In this context, underserved populations typically include groups with lower socioeconomic status, marginalised ethnic or indigenous communities, people living in rural or remote areas, and individuals facing barriers to healthcare access. Multiple studies have shown that factors such as vaccine hesitancy, limited access to vaccination sites, and sociocultural beliefs can influence vaccine uptake [8,9]. However, spatial analyses in other settings have demonstrated that these factors often cluster geographically and this may lead to localised pockets of lower immunisation coverage. In addition, there has been limited examination of the nationwide spatial distribution of COVID-19 immunisation coverage, which could inform targeted interventions to reduce inequities. Analyses that ignore geography can mask important local variation by averaging across populations. Spatial approaches retain information on location, revealing where inequities in vaccination coverage are concentrated and where targeted public health responses may be most effective. Understanding these patterns is critical for evaluating whether vaccination strategies reach all communities equitably and for identifying mechanisms through which social and structural determinants influence vaccine uptake [10].

Immunisation coverage has declined in many developed nations, including NZ, following the onset of the COVID-19 pandemic in 2020 [5,11,12]. While an extensive body of research has identified the importance of tailored communication strategies to diverse communities [13,14], data on geospatial immunisation coverage are limited [14]. While differences in immunisation coverage related to area-level deprivation and ethnicity have been well documented in high-income countries, only a few studies examine the clustering of low- or high immunisation coverage areas over space and time. Such clustering may occur independently of deprivation or ethnicity and is highly relevant for outbreak risk, as localised areas of under-immunisation can facilitate disease spread despite high national coverage. In NZ, a spatiotemporal analysis from 2005 to 2017 identified clustering of low childhood immunisation coverage in more densely populated areas [5,6]. Understanding whether COVID-19 introduced new geographic disparities, or whether these trends mirror existing gaps in childhood immunisation, provides valuable insight into the persistence and dynamics of under-immunisation and helps inform more targeted public health responses. Achieving equitable COVID-19 immunisation coverage, which may be the result of inaccessible healthcare or socio-economic barriers or both [15] requires good visibility of the geospatial patterns in the disparities i.e. knowing where the problems are. Previous geospatial analyses in NZ have revealed clusters of suboptimal coverage or under-vaccinated areas, often coinciding with regions experiencing higher levels of deprivation and social vulnerability [3,5,8].

Despite significant efforts to achieve widespread COVID-19 immunisation, data on spatial variation, particularly of unvaccinated populations are limited. Our study uses robust nationwide data over one year in 2022, to conduct an analysis of adult COVID-19 immunisation coverage by key sociodemographic and area-level characteristics (i.e. age group, sex, ethnicity, area-level deprivation and the interaction between ethnicity and area-level deprivation). It also examines spatial variation in vaccine uptake over time, visualised in an interactive online map. Finally, it then aims to examine the sociodemographic characteristics and spatiotemporal patterning of unvaccinated adults. We hypothesis that that immunisation coverage would be lowest for younger ages as well as those underserved populations including in areas of higher area-level deprivation, Māori and Pasifika populations as well as in more rural areas.

2. Methods

2.1. Study design, participants and settings

We conducted a nationwide geospatial study. Population data and outcomes were derived from the Integrated Data Infrastructure (IDI), which is a large nationwide secured data repository holding linked de-identified individual- and household-level microdata [16]. It is curated and managed by Stats NZ and all research conducted with the data repository must be for the public good and the improvement of outcomes for New Zealanders [16,17]. The study period was from 1st January 2022 to 31st December 2022. The study population was identified based on the Estimated Resident Population (ERP) dataset available in the IDI that contains basic anonymised information about individuals with evidence of health, taxes or education activity in NZ. The final population consisted of 4,098,447 adults aged 18 years and over as of June 30th, 2021.

2.2. Outcome and non-geospatial explanatory variables

We had two main outcomes of interest. First, doses of COVID-19 vaccine, we included doses of any type of vaccine, and these data were recorded and identified within COVID-19 Immunisation Register (CIR) within the IDI. We also used the IDI to determine whether the individual was recorded as having a positive identification and notified infection with SARS-CoV-2 by PCR during the study period provided by the New Zealand Ministry of Health.

During the study period, vaccine eligibility for adults in New Zealand was phased in by job role and age group. The rollout began in February 2021 with border and managed isolation workers and frontline health staff, before expanding to high-risk adults in March and April 2021. Eligibility then widened to adults aged 60 years and older and then to those aged 55 years and older in July/August 2021, and to all adults aged 16 years and older nationwide from September 2021. A booster (third dose) programme was introduced in November 2021, initially recommended for adults aged 18 years and older, to be given six months after the second dose. In February 2022, the recommended interval between the second dose and the booster was shortened to accelerate uptake in the context of the Omicron outbreak.

In this study, outcomes were stratified by age at the end of January 2022, total response ethnicity (European/Other, Māori, Pasifika, Asian) and area deprivation based on area of residence (quintiles and deciles, Q1/D1 – least deprived, Q5/D10 – most deprived). We used total response ethnicity, which records every ethnic group that an individual identifies with. This means a person can be counted in more than one ethnic category. Accordingly, the total count across ethnic groups may exceed the actual number of participants, and the sum of percentages can exceed 100 %. Results therefore represent ethnic responses, not mutually exclusive individuals.

2.3. Defining environmental exposure and geospatial analysis

We examined monthly geospatial coverage of vaccine dose and infection during the Omicron wave from January 1st 2022 to 31st December 2022 by combining vaccine uptake events and positive tests for individuals and providing rates aggregated by Statistical Area 2 (SA2). SA2s aim to reflect communities that interact together socially and economically with similar-sized populations in populated areas (2000–4000 residents in cities, 1000–3000 in towns, and fewer than 1000 in more sparsely populated but larger areas) [18]. Even though spatially more detailed data are available SA2 ensures lasting data confidentiality while showing spatial variations. We also linked SA2 to their respective urban/rural classification using five-level Geographic Classification for Health [19]. The Geographical Classification for Health (GCH) is comprised of five categories, two urban and three rural, that reflect degrees of reducing urban influence and increasing rurality. They are based on a scale from 'Urban 1' to 'Urban 2' based on population size, and from "Rural 1′ to 'Rural 3′ based on drive time to their closest major, large, medium, and small1 urban areas.

2.4. Statistical analyses

First, immunisation coverage (receipt of a particular number of doses as a proportion of the total population) was examined by individual month for 2022 by age group, sex, ethnicity, area-level deprivation and the interaction between ethnicity and area-level deprivation. It was then mapped at the SA2 level for overall rates (%) and then by population category. This data was then plotted on an interactive map (the user can specify what data is plotted) at the SA2 level.

Second, we examined spatial and spatiotemporal variation in immunisation coverage using three types of analyses for unvaccinated adults. First, we mapped the proportion of the population who received zero doses (unvaccinated adults) by SA2 using a 12-month average of monthly data from January 2022 to December 2022. Second, we carried out an optimised hotspot analysis of COVID-19 immunisation rates from January 2022 to December 2022 for those unvaccinated adults using the 12-month average data at the area-level (Statistical Area 2). This method uses the Getis-Ord Gi* statistic to detect statistically significant spatial clusters of high or low values in the dataset [20]. Third, consistent with previous evidence, we then focused on the identification of spatio-temporal patterns using Emerging Hot Spot Analysis (EHSA) [10,21]. This analysis aimed to identify clusters of areas that share similar patterns in their characteristic(s) both spatially and temporally. It combines Getis-Ord Gi* (spatial hot spot analysis) exploring spatial autocorrelation in the data with Mann-Kendall test for monotonic trends [22]. Data were transformed into a space-time cube and the inference is based on the analysis comparing patterns within a selected spatial neighbourhood and time lags in the neighbourhood. The conceptualisation of spatial relationships was based on spatial contiguity (edges only) with a neighbourhood step of two used in the settings of the analysis. This means we were evaluating neighbours sharing a border (SA2). The significance threshold of EHSA was set as 0.01 after 199 simulations [22]. ArcGIS Pro was used for both analysis and visualisation of results. Finally, we examined if ethnicity, area-level deprivation and urban/rural classification, were related to the likelihood of being classified as a hot spot using logistic regression in STATA V17 [23].

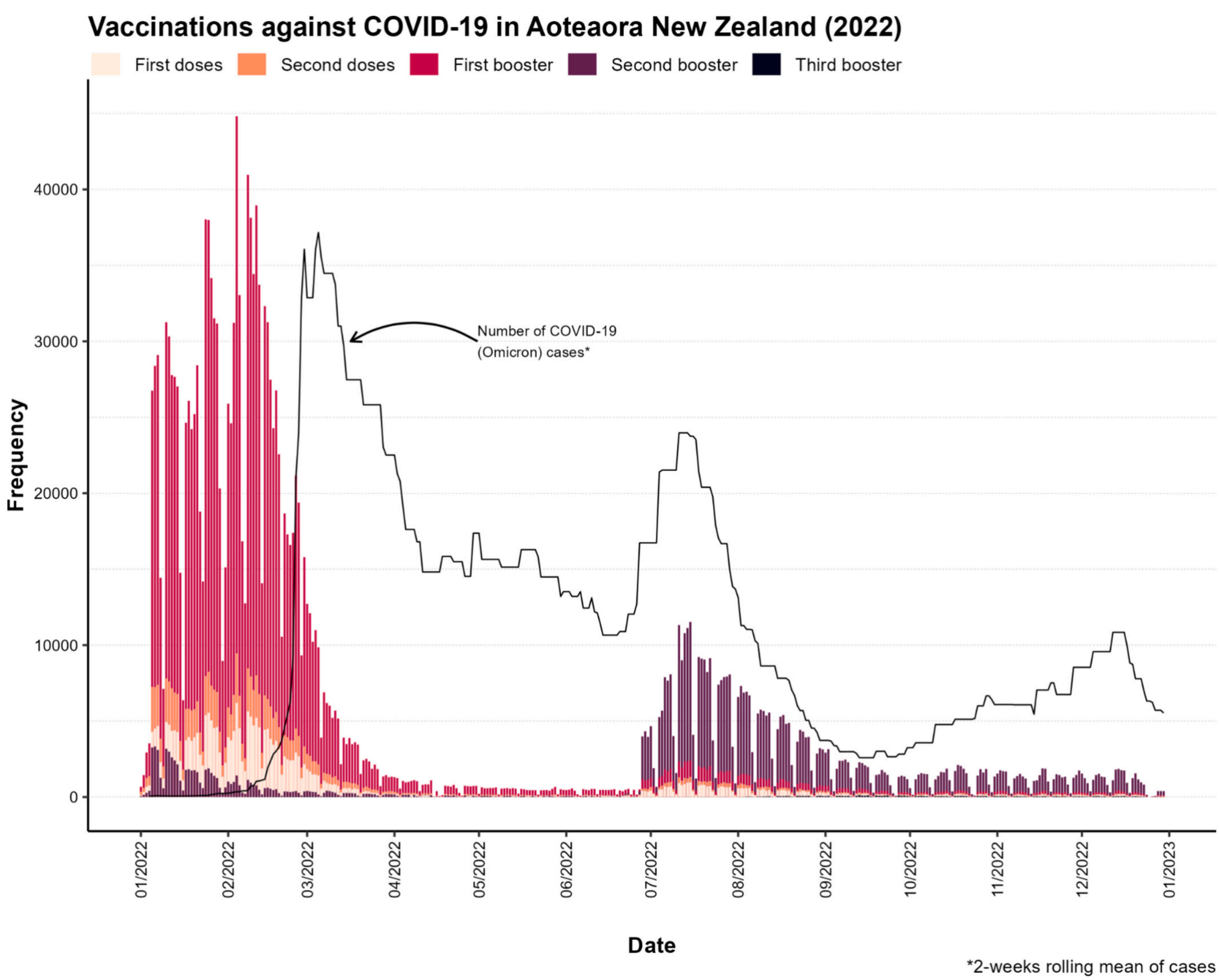

Fig. 1. Number of COVID-19 vaccines administered in Aotearoa New Zealand by dose number and COVID-19 cases in 2022.

3. Results

3.1. Examining variation in immunisation rates

Most of the population had received at least two vaccine doses prior to January 2022, and by March 1st, 2022, when the number of COVID-19 cases had begun to substantially increase, most had received three doses of COVID-19 vaccine. A second smaller peak of vaccination activity occurred in July and August 2022, driven by fourth (second booster) doses (Fig. 1).

3.1.1. COVID-19 immunisation coverage by age group

Fig. 2 shows the difference in vaccination by age group over time. At the start of the study period (1 Jan 2022) the highest coverage with three doses of vaccine was among those aged 75 years or more (Fig. 2). Over 60 % of those aged 65–74 had also received three doses. Much smaller proportions, less than 20 %, of younger people (18–34) had received a third dose but most had received at least 2 doses (70–80 %). Uptake of third doses increased rapidly in March and April, with coverage at 80–90 % for those over 65 years of age and 50–60 % in the youngest age groups (18–34). Median age groups were in between these values. Those who didn't receive any doses remained consistent in terms of percentage throughout the study period where was minimal change in coverage from April to December 2022.

3.1.2. COVID-19 immunisation coverage stratified by age group, ethnicity and area-level deprivation

We examined vaccine coverage at the end of the calendar month by age (18–24, 25–34, 35–44, 45–54, 55–64, 65–74, 75+ years), ethnicity (European/Other, Māori, Pasifika, Asian) and area-level deprivation as well as the interaction between ethnicity and area-level deprivation. These other data are shown in the online supplementary materials (Fig. S1-S14). Results are reported using total response ethnicity. Individuals may be represented in more than one ethnic group; therefore, the sum of percentages across groups can exceed 100 %.

Key foci of these analyses include a large increase in third dose (booster) uptake in January and February prior to widespread community transmission of COVID-19 infection in March. When examined by age, among the oldest adults, at highest risk from severe COVID-19 infection, uptake of booster doses was highest. When examined by ethnicity, there was a strong age-related gradient with lower coverage in younger age groups which was especially pronounced for Māori and Pasifika. For ethnicity, at the start of the study period, 80 % of Māori and just over 85 % of Pasifika people had received at least two doses of vaccine, but only around 20 % had received their third (booster) dose. In contrast, the proportion of Europeans/Other people who had received at least two doses was highest (just under 90 %) as was the who had received booster (third) doses (35 %) with intermediate uptake among New Zealanders with Asian ethnicity (85 % and 20 %). Over time, uptake for all ethnic groups was rapid in March and April with little or no increase from April to December 2022. Finally for ethnicity, the proportion of Māori adults over 65 years who received booster doses was 75–80 %, about 10 % less than Europeans in the same age groups and among Pasifika was 65 % and among New Zealanders with Asian ethnicity over 65 years was 70 %.

When examined by area-level deprivation, there was a small gradient

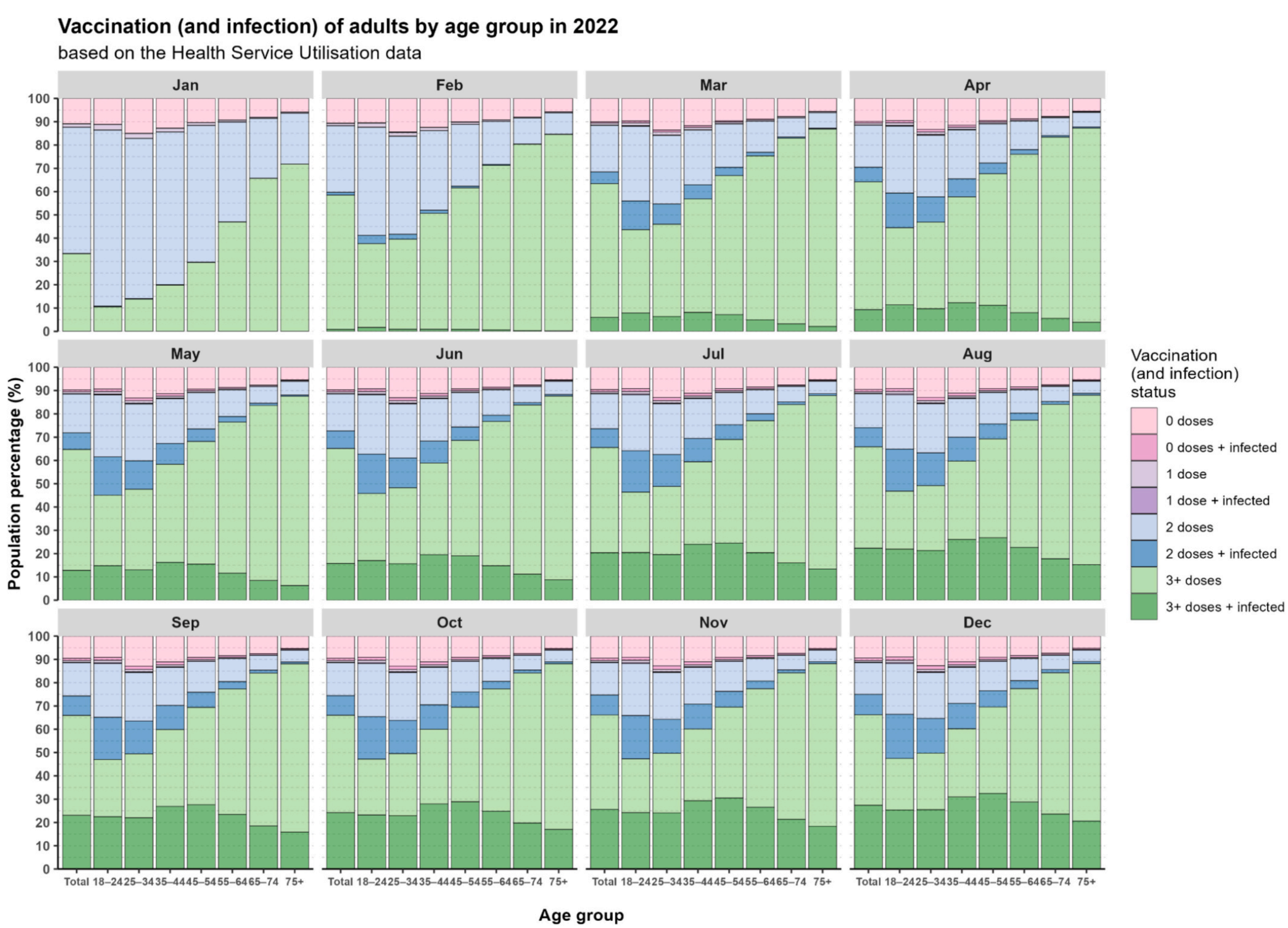

Fig. 2. Vaccination and infection of adults in NZ by age group in 2022 by calendar month.

of difference in coverage. Those residing in more deprived areas (Quintile 5) had a slightly lower proportion of two-dose vaccinated adults – 85 % compared with over 90 % of those living in the least deprived areas (Quintile 1). For booster doses, the disparity was greater (60 % for adults residing in the highest deprivation areas (Quintile 5) compared to 75 % of those living in the lowest deprivation areas (Quintile 1)). The percentage of the population who were unvaccinated remained consistent in terms of percentage in younger age groups and the most deprived areas over time. Other results including those for each ethnicity by area-level deprivation are presented in the online supplementary materials.

3.2. Examining spatial variation in immunisation rates

Our data are also available to explore interactively by Statistical Area 2 (SA2) geospatially here. A screenshot of the interactive map and data available to explore are displayed in Fig. 3. The maps display topics you can explore including infection rates (%), vaccination rates (%), and monthly changes in both (%). You can scroll down or up to move through individual topics and the data is prepared to show ethnic-specific rates of all measures that you can access by simply clicking on the ethnicity label on the left-hand side of the interactive map. Please note that some figures are static screenshots of interactive maps developed for policy use; place names and labels update dynamically and are fully readable when users zoom to appropriate spatial scales in the interactive version.

3.3. Examining unvaccinated adult population patterns

This study also examined those populations who were or remained unvaccinated throughout the study period of 2022. In contrast to the rapid uptake of third doses in the first few months of 2022, the percentage of those unvaccinated (no recorded doses) within each SA2 showed minimal change over the 12 months between January and December 2022 (Table 1). In January 2022 9.85 % of adults were unvaccinated; by November 2022 this percentage had decreased by 0.44 of a percentage point to 9.41 %. While there was a clear social gradient in unvaccinated adults, with the highest proportion in the most deprived areas of the country. In addition, these percentages remained relatively constant within strata of deprivation over time. Finally, when examined by urban and rural classification there was a clear gradient, with those in the most rural areas (rural 3) having the highest proportion of unvaccinated adults which changed very little during 2022.

Table 2 shows the distribution of unvaccinated adults stratified by age and ethnicity. In general, New Zealanders with Asian ethnicity had the lowest percentage of unvaccinated adults across age groups while the Māori population had the highest proportion who were not vaccinated in 2022. When examined by age, the overall pattern was of the highest proportion of unvaccinated adults being in the 25–44 years age group and the lowest proportion in those over the age of 65 years, however this differed by ethnicity. Among adults of Asian ethnicity, who had the lowest percentage unvaccinated in all age groups, there was a progressive increase in the percentage unvaccinated from 3.89 % in those 18–24 years to 6.30 % in those over 65 years.

Table 3 focuses on adults >65 years by ethnicity, showing changes in the proportion who had received three and no doses in January, March and December 2022. In January, the proportion of the population who had received three doses was highest in those of European ethnicity (71.0 %), with all other ethnicities being more than 10 percentage points lower, from 55.1 % (MEELA) to 60.4 % (Māori). Between January and March, the greatest increase in the percentage with 3 doses was among Asian adults (24.2 %), with increases in the percentage of adults >65 years who had received three doses more than two-fold greater than European in all other ethnicities, such that the total percentage with at least three doses was similar across ethnic groups by March. In contrast, between March and November, the percentage of European adults >65 years who had received three doses increased by 8.1 % to 87.0 %, but by less than 3 % in all other ethnicities. Therefore, the three dose coverage in Europeans was 87.0 %, with Asian adults next highest (83.5 %) and MEELA lowest (78.5 %). With respect to unimmunised adults (with no doses) patterns by age were compared using the ratio of the percentage of adults >65 years with no doses to the highest percentage with no doses in younger age groups. Notably, this ratio was below one in all ethnic groups (from 0.68 in Māori to 0.98 in Pacific) except for Asian adults >65 years for whom the ratio was 1.29. This is consistent with the pattern shown in Table 2 for Asian adults, where although adults >65

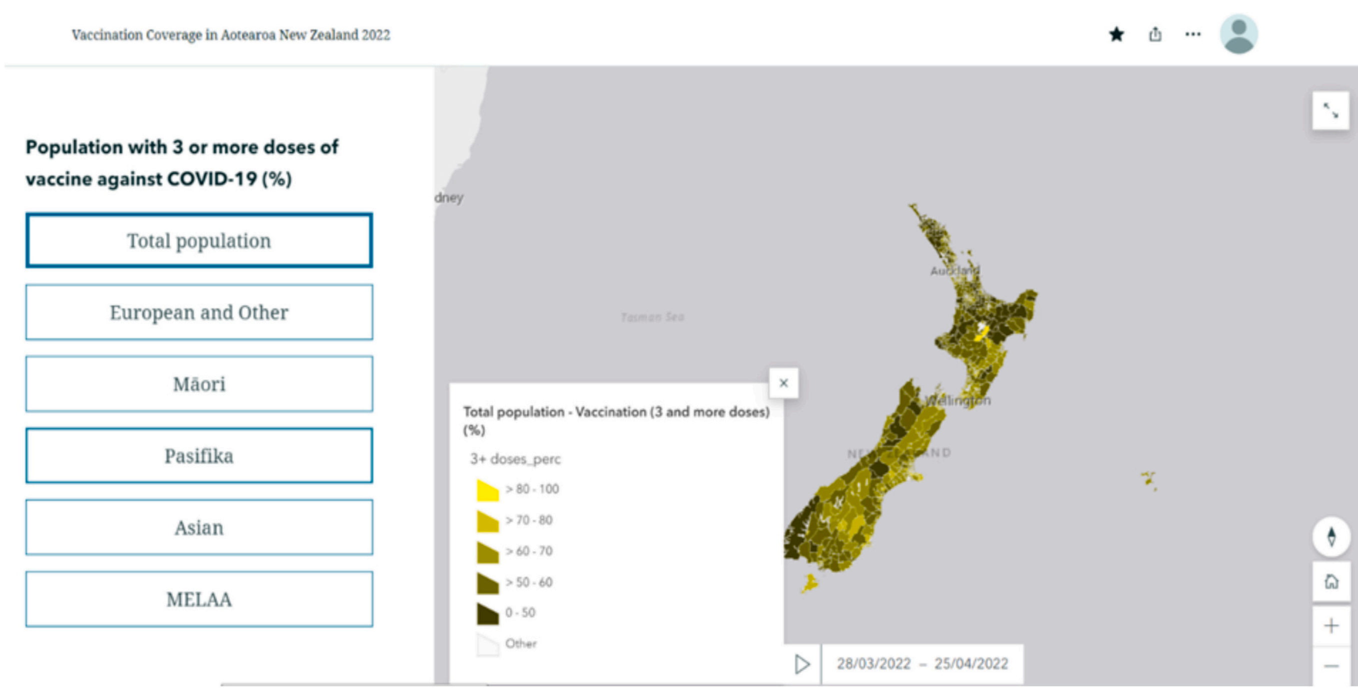

Fig. 3. A screenshot of our interactive map visualising infection and vaccination (3 or more doses) by Statistical Area 2 over time.

Table 1
Percentage of the population unvaccinated by month in New Zealand by key sociodemographic and area-level characteristics.

	Jan	March	May	July	Sep	Nov
Overall	9.85	9.46	9.42	9.43	9.42	9.41
Area-level deprivation						
Decile 1 (least	6.90	6.74	6.72	6.71	6.70	6.68
deprived)	7.92	7.73	7.70	7.67	7.67	7.66
D2	8.38	8.15	8.09	8.08	8.10	8.07
D3	8.71	8.42	8.39	8.37	8.35	8.35
D4	9.69	9.38	9.35	9.33	9.32	9.32
D5	10.42	10.05	10.02	9.98	9.98	9.97
D6	10.17	9.75	9.71	9.68	9.68	9.67
D7	10.46	9.98	9.93	9.91	9.83	9.87
D8	11.85	11.22	11.22	11.15	11.16	11.11
D9	14.04	13.18	13.10	13.04	13.02	13.02
Decile 10 (most						
deprived)						
Urban/rural						
Urban 1	7.77	7.45	7.42	7.39	7.38	7.38
Urban 2	10.85	10.37	10.32	10.27	10.26	10.24
Rural 1	12.61	12.12	12.08	12.03	12.03	12.02
Rural 2	14.55	14.06	14.03	14.01	13.99	14.01
Rural 3	16.93	16.46	16.27	16.28	16.37	16.23
Ethnicity[1]						
Māori						
Q1 (lowest	7.45	7.25	7.21	7.20	7.19	7.19
proportion)	8.67	8.39	8.35	8.32	8.32	8.31
Q2	10.12	9.69	9.67	9.64	9.60	9.60
Q3	13.31	12.63	12.59	12.51	12.52	12.49
Q4 (highest						
proportion)	10.00	9.69	9.67	9.65	9.65	9.64
Pacific	9.83	9.49	9.45	9.42	9.41	9.41
Q1 (lowest	10.30	9.85	9.81	9.77	9.76	9.75
proportion)	8.98	8.48	8.41	8.38	8.35	8.34
Q2						
Q3	13.01	12.57	12.51	12.50	12.50	12.47
Q4 (highest	10.33	9.90	9.88	9.84	9.83	9.82
proportion)	8.64	8.25	8.23	8.17	8.17	8.15
Asian	7.13	6.82	6.77	6.75	6.74	6.74
Q1 (lowest						
proportion)						
Q2						
Q3						
Q4 (highest						
proportion)						

[1]Percentages are based on total response ethnicity. Individuals may be counted in more than one ethnic group.

years had the highest coverage with three doses in any ethnic group, when Asian adults were examined separately, those >65 years were less likely to have received 3 doses than younger age groups.

When examined by region in Fig. 4 and using the optimised hot-spot analysis in Fig. 5, several patterns emerged. Largely urban areas of the country were identified as cold spots (i.e. statistically significant spatial clusters of low proportions of unvaccinated adults at the SA2 level) while several more rural regions were identified as hot spots (i.e., statistically significant spatial clusters of high proportions of unvaccinated adults at the SA2 level). Urban centres including Auckland, Christchurch, Dunedin, Hamilton, and Wellington were consistently identified as cold spots in Fig. 5. In contrast, the North-West of South Island and large areas of the North Island including areas such as Northland, Taranaki and Bay of Plenty were identified as hotspots with a larger percentage of SA2s with high proportions of unvaccinated adults at the SA2 level. An emerging hotspot analysis (Online Supplementary Fig. S15) confirmed these trends over the one-year study period. Only a small number of emerging hot spots and cold spots were observed, highlighting stability in geographic disparities in vaccination coverage over time.

Table 2
Monthly percentage of the population with no recorded doses by age and ethnicity in New Zealand.

	Jan	Mar	May	Jul	Sep	Nov
Overall						
18–24	8.68	7.79	7.70	7.67	7.65	7.68
25–44	11.44	10.88	10.80	10.77	10.74	10.73
45–64	9.35	9.10	9.05	9.02	9.02	9.03
65+	8.34	8.20	8.20	8.17	8.16	8.18
European and Other						
18–24	7.69	7.11	7.06	7.03	7.01	7.01
25–44	10.9	10.42	10.37	10.33	10.31	10.31
45–64	8.93	8.72	8.69	8.68	8.67	8.66
65+	7.78	7.69	7.67	7.65	7.65	7.65
Māori						
18–24	14.52	12.91	12.79	12.72	12.68	12.66
25–44	18.03	16.66	16.56	16.48	16.43	16.41
45–64	13.19	12.66	12.62	12.59	12.58	12.57
65+	11.01	10.83	10.80	10.77	10.76	10.76
Pasifika						
18–24	9.37	8.15	8.05	7.98	7.94	7.93
25–44	11.37	10.41	10.32	10.23	10.18	10.15
45–64	9.57	9.22	9.19	9.14	9.11	9.11
65+	10.30	10.10	10.06	10.03	10.02	10.01
Asian						
18–24	3.96	3.72	3.72	3.70	3.70	3.69
25–44	4.30	4.10	4.06	4.03	4.02	4.01
45–64	5.04	4.91	4.89	4.87	4.86	4.86
65+	6.64	6.42	6.35	6.31	6.31	6.30
MELAA						
18–24	6.78	6.04	6.01	5.97	6.01	5.97
25–44	8.72	8.17	8.11	8.07	8.04	8.03
45–64	10.23	9.91	9.86	9.80	9.79	9.79
65+	9.66	9.43	9.42	9.40	9.39	9.40

Note: MELAA = Middle Eastern/Latin American/African. Percentages are based on total response ethnicity. Individuals may be counted in more than one ethnic group.

3.4. Investigating what factors are associated with being a SA2 unvaccinated adult hot-spot

Finally, we examined how area-level deprivation, ethnicity and rurality were associated with a SA2 being classified as a hot spot of unvaccinated adults (Table 4). Hot spots were defined based on the 95 % (light pink) and 99 % (dark pink) hot-spot clusters identified in Fig. 5. There were significantly increasing odds of an SA2 being a hot spot of unvaccinated adults (the highest proportion of zero dose) with increasing rurality and area-level deprivation. There was an exception with rural 3 (most rural) SA2s but this may be related to lack of precision due to low population numbers. Finally, for ethnicity, as the proportion of the SA2 identified as Māori increased so did the likelihood of a hot spot of unvaccinated adults. In contrast, as the proportion of the SA2 identifying as Pasifika and Asian increased the odds of being an unvaccinated adult hot spot decreased.

4. Discussion

This nationwide geospatial study adds to international evidence that has examined COVID-19 vaccine uptake in adults. This study in Aotearoa New Zealand had several features differentiating it from previous studies of COVID-19 vaccine uptake elsewhere. First, data on coverage were derived from a national electronic register rather than regional surveys and second patterns by age, sex, ethnicity and area-level deprivation of residence were examined geospatially. Third, there was a focus on patterns of receipt of third dose (booster) versus unvaccinated adults during first emergence of community transmission in 2022. The lack of community transmission prior to widespread community transmission of the Omicron variant related to rigorous border controls and non-pharmaceutical interventions alongside high immunisation uptake resulted in NZ having one of the lowest pandemic

Table 3
The proportion of adults >65 years who were unvaccinated and those who had received three doses in January, March and December 2022 by ethnicity in New Zealand.

Ethnicity groups[2]	Jan (%)	March (%)	Jan to March Increase/ Decrease	March to November (%) (Increase/ Decrease)	Ratio by ethnic group[1]	Ratio of % with no doses in oldest age group / highest % in younger age groups
European/Other (three doses)	71.0	78.9	+7.9	87.0 (+8.1)	1.00	
European/Other (zero doses)	7.78	7.69	−0.09	7.65 (−0.04)	1.00	7.65/10.31 = 0.74
Māori (three doses)	60.4	78.9	+18.5	80.7 (+1.8)	0.93	
Māori (zero doses)	11.01	10.83	−0.08	10.76 (−0.15)	1.41	10.76/16.41 = 0.66
Pasifika (three doses)	56.8	77.2	+21.6	80.2 (+3.4)	0.92	
Pasifika (zero doses)	10.3	10.1	−0.20	10.01 (−0.01)	1.31	10.01/10.15 = 0.98
Asian (three doses)	56.4	80.6	+24.2	83.5 (+ 2.9)	0.95	
Asian (zero doses)	6.64	6.42	−0.22	6.31 (−0.11)	0.82	6.30/4.86 = 1.29
MELAA (three doses)	55.1	76.0	+20.9	78.5 (+2.5)	0.90	
MELAA (zero doses)	9.66	9.43	−0.23	9.40 (−0.03)	1.23	9.40/9.79 = 0.96

Note: MELAA = Middle Eastern/Latin American/African.
[1]Compared with European/Other set as a ratio of 1.0.
[2]Percentages are based on total response ethnicity. Individuals may be counted in more than one ethnic group.

mortality rates in the world [24]. Our study highlights that by the end of February 2022, over half the adult NZ population and around four out of five adults aged 65 years and over had received a third vaccine dose, known to protect against severe disease and death in the early Omicron era [25]. This contrasts with other countries around the globe where mortality due to Omicron was much higher often in the context of high population density and relatively low immunisation coverage among the elderly at highest risk [26,27]. In this study, those aged 18–24 and 25–34 had much lesser uptake of the third vaccine dose. However, this may be related to the older population becoming eligible for the booster (third dose) much earlier, to young people becoming infected and therefore not eligible for a booster until later, or to a lack of engagement past the mandatory first two doses.

Globally, COVID-19 vaccination uptake has shown substantial variation across countries and between population groups; evidence that is consistent with evidence presented in this study which revealed inequities by age, ethnicity and area-level deprivation. For instance, in this study, fewer Māori and Pasifika had a third dose when compared to European/Other and a lower percentage of the population in the most deprived areas had received a third dose when compared to the least deprived areas, something that was persistent across ethnic groups. This is consistent with previous evidence that has also shown inequity in immunisation coverage in NZ [5,28] and internationally with studies from Europe, North America and Australia demonstrating lower uptake in socially disadvantaged communities, ethnic minority groups, and rural or remote populations, even in settings with high overall vaccine availability [29]. For instance, previous research has shown significant 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 [30]. This also supports NZ evidence where, for instance, in a retrospective cohort study of pregnant women who delivered a baby between 2013 and 2018, compared to NZ European or Other women, Māori and Pacific women had lower odds of receiving maternal pertussis and influenza immunisations during pregnancy [12]. While these findings corroborate existing evidence seldom has research considered how these inequities manifest geospatially, especially using nationwide data for COVID-19 vaccination. Examining geospatial patterns are important because coverage in some areas can be unacceptably lower than average putting whole communities at much higher risk of disease than a national summary indicates.

While COVID-19 immunisation coverage in Aotearoa New Zealand was high and increased from January 2022 to December 2022 which included community transmission and the Omicron outbreak, there was significant spatial variation. The most notable difference geospatially was when our data were examined by rural or urban classification with significantly higher coverage in urban areas. This supports previous research which showed that between June and December 2021 rural vaccination rates lagged behind urban rates, despite an earlier rapid rural uptake [31]. When our study examined unvaccinated adults, the differences in uptake rates between the most remote and most urban communities were most marked in the North Island with several hotspots of unvaccinated adults evident in what were largely rural areas. This was in keeping with previous evidence of lower-than-expected immunisation in similar areas among children [5,6]. For instance, vulnerability based on sociocultural factors and populations aged 65+ was higher in previous research in areas such as the East Cape region and major cities of the North Island, influenced by significant proportions of different ethnicities in these areas [3]. To the authors' knowledge, this study provides the first nationwide investigation internationally to demonstrate significant spatial clustering of COVID-19 immunisation coverage. Further research is needed from other contexts internationally to examine the spatial clustering of under-immunised communities to reinforce our concerns that national coverage metrics may mask localised vulnerability.

Suboptimal immunisation coverage is a complex issue that is increasingly affecting many countries around the world, with no single solution [32]. Improving immunisation coverage requires a multifaceted approach with interventions at the structural, social and behavioural levels [11,33]; part of this is a better understanding of those who and in what areas do individuals not get immunised. In our study, a higher percentage of unvaccinated adults was seen in younger age groups (aged 18–34 years) for Māori and in older people (aged 75+) for Pasifika. However, when relative differences in age-specific uptake were examined, it was apparent that among New Zealanders with Asian ethnicity, a higher proportion of unvaccinated adults in the oldest rather than the youngest adults, even though overall uptake was high contrasted with patterns among all other ethnic groups. Our results also demonstrate a gradient by area-level deprivation with less uptake of a third vaccine dose in the most deprived areas for all ethnic groups, but a pattern that was most pronounced for Māori. Further research is needed to explore the populations who and remained were unvaccinated adults. Interestingly, in this study, the percentage of the population who received zero doses remained consistent throughout the year of study and was also strongly patterned by rural-urban gradient with a lower proportion of unvaccinated adults in urban areas relative to rural areas. This likely reflects a combination of factors including structural inequity in access to vaccination services [7], vaccine hesitancy [34] as well as broader differences in regional geography and socio-demographic differences in rural communities [31] which require further research.

The rigour of this study is strengthened using nationwide data in the IDI data to capture as much of the population as possible and by using a

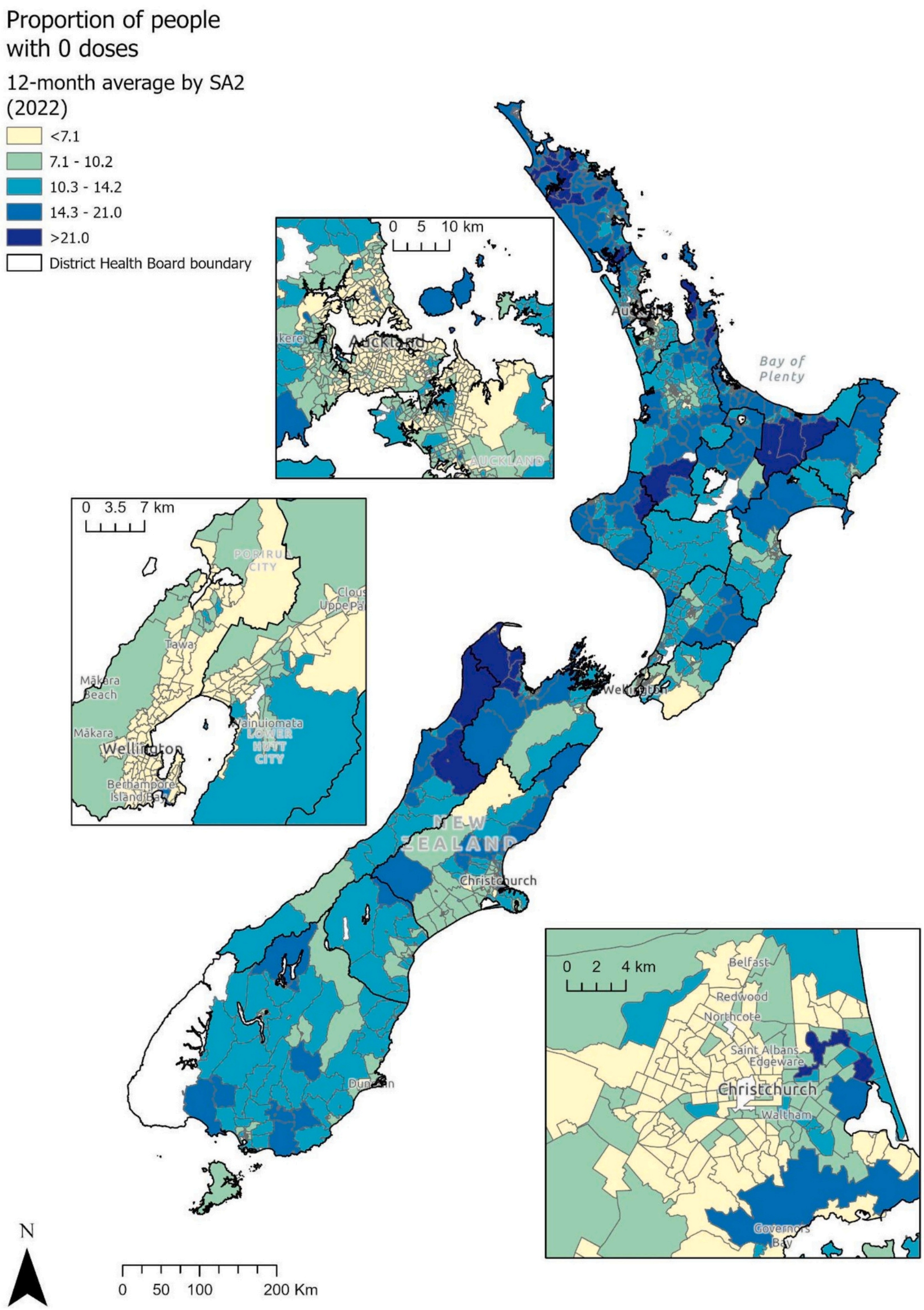

Fig. 4. The percentage of population who received zero dose (unvaccinated adults) by Statistical Area 2 (data are 12-month average from January 2022 to December 2022).

novel geospatial lens. However, there are several limitations which should be considered when interpreting findings. First, due to the granularity of the data we were unable to show immunisation coverage at a finer geographical scale which does not make comparisons based on area-level deprivation and accessibility feasible. For instance, future work would benefit from investigating coverage at a finer geographical scale however, we were unable to do so in this study due to potential identification/confidentiality issues. Our study assumed limited mobility of the population to determine a population of interest both on a national and local scale; however, residential mobility is dynamic and affects population counts in smaller areas. Furthermore, the evidence suggests that residential mobility can influence how people interact with health services [35]. The selection of the appropriate population (and denominators) is a common challenge of (not only) health-oriented research. Our population was based on the Estimated Resident Population dataset available in the IDI that provides the best measure of the

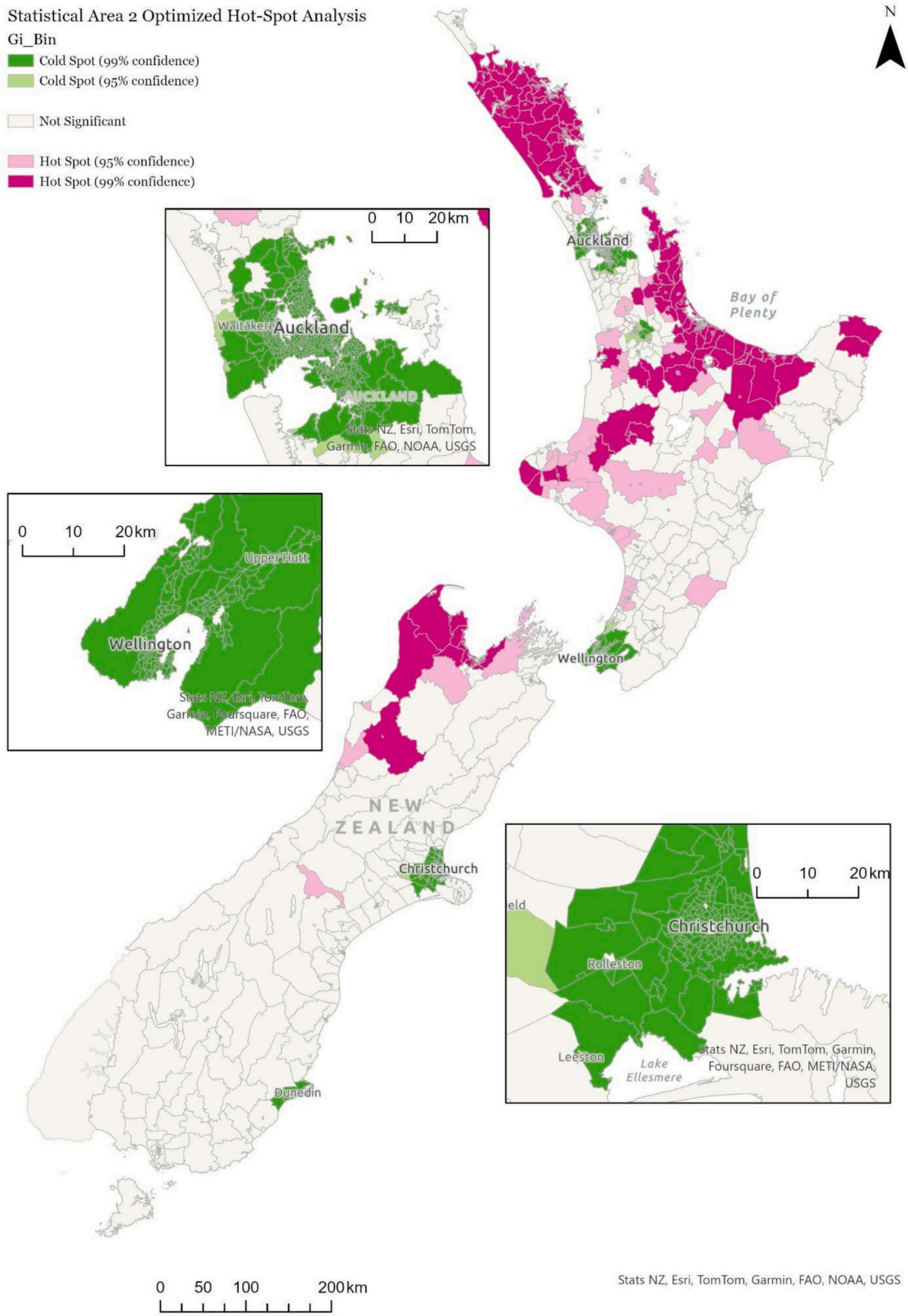

Fig. 5. An optimised hotspot analysis of COVID-19 immunisation rates from January 2022 to December 2022 for those who received zero dose (unvaccinated adults) by Statistical Area 2 (black lines represent District Health Board boundaries).

Table 4
Investigating the association between unvaccinated adult (zero-dose) hot spots (defined as 95 % and 99 % hot spots) and urban/rural classification, area-level deprivation and ethnicity in New Zealand.

	Odds ratio	[95 % confidence interval]	P > z
Urban/rural classification			
Urban 1 (most urban)	Reference		
Urban 2	**2.35**	**[1.58, 3.46]**	**<0.001**
Rural 1	**2.53**	**[1.68, 3.79]**	**<0.001**
Rural 2	**2.62**	**[1.59, 4.33]**	**<0.001**
Rural 3 (most rural)	2.12	[0.92, 4.88]	= 0.076
NZDep 2018 quintile			
Quintile 1 (Q1) (least deprived)	Reference		
Q2	1.60	[0.99, 2.58]	=0.051
Q3	**2.80**	**[1.78, 4.41]**	**<0.001**
Q4	**3.33**	**[1.40, 3.87]**	**=0.001**
Q5 (most deprived)	**3.55**	**[1.92, 6.55]**	**<0.001**
Ethnicity			
Proportion of SA2 Māori	**1.05**	**[1.03, 1.07]**	**<0.001**
Proportion of SA2 Pasifika	**0.86**	**[0.81, 0.91]**	**<0.001**
Proportion of SA2 Asian	**0.94**	**[0.92, 0.96]**	**<0.001**

Note: area under ROC curve for model = 0.86.

population that usually lives in New Zealand at a given reference date. While the IDI is an invaluable data source for NZ researchers, it still relies on data reported by individual local providers and suffers from weaknesses expected of an administrative data resource capturing mostly the (government) service use such as data quality issues, missing qualitative data, or missing individuals who do not access government services [36,37]. The critical areas of improvement include the appropriate capturing of ethnicity (including Māori iwi (tribe) affiliation), data on rainbow communities, disability, and dwellings.

5. Conclusion

In summary, this nationwide geospatial study is, to the authors' knowledge, one of the first to investigate spatial variation in COVID-19 immunisation coverage over an extended period. Our findings will have important implications for shaping policy and intervention in future pandemics but also to better understand how immunisation coverage developed in 2022 during the COVID-19 pandemic. Internationally, we add to evidence by showing how geospatial analyses can be used to visualise and provide an in-depth examination of immunisation coverage in a COVID-19 infection naïve population. Further research on the spatial clustering of vaccination is urgently needed in different contexts around the world, to confirm our findings however, our geospatial analyses have the potential to inform and thus minimise the inequitable regional differences in healthcare provision and immunisation coverage, in NZ and other countries.

CRediT authorship contribution statement

M. Hobbs: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **L. Marek:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **J. Wiki:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **J. Paynter:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **N. Nghiem:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **B. Liu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **P. McIntyre:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Disclaimer

Access to the data used in this study was provided by Stats NZ under conditions designed to give effect to the security and confidentiality provisions of the Data and Statistics Act 2022. The results presented in this study are the work of the author, not Stats NZ or individual data suppliers. These results are not official statistics. They have been created for research purposes from the Integrated Data Infrastructure (IDI), which is carefully managed by Stats NZ. For more information about the IDI, please visit https://www.stats.govt.nz/integrated-data/.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.vaccine.2025.128165.

Data availability

The authors do not have permission to share data.

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