QUANTITATIVE RESEARCH

Applications of geographic information systems in public health: A geospatial approach to analyzing MMR immunization uptake in Alberta

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ABSTRACT

OBJECTIVE: This study evaluates the temporal, spatial, and spatio-temporal variation of immunization rates for measles, mumps and rubella (MMR) immunization in the province of Alberta. The study uses yearly immunization rate data for Health Zones and Local Geographic Areas (2004–2012), which were obtained from Alberta Health's Interactive Health Data Application (IHDA).

METHODS: Spatial analyses include a global spatial analysis, Moran's I, and local indicators of spatial association (LISA) analysis – Getis and Ord's G* – to identify clusters of high or low immunization rates. Spatial methods are then applied to a time series analysis to examine how the immunization rates change over time in conjunction with space.

RESULTS: Mapped results indicate decreasing immunization rates over time for the majority of the province where most local geographic areas (LGAs) fall short of the 95% herd immunity threshold. Clusters of high immunization rates in the metropolitan centres, and clusters of low immunization rates in the southern and northern region of the province exist spatially and spatio-temporally. Over time, the high rate clusters are decreasing in size and the low rate clusters are increasing.

CONCLUSION: This research provides a localized geographic approach to assessing MMR immunization rates in Alberta. Findings from this research can be used to target public health interventions to specific areas that exhibit the lowest immunization rates. These results can also be used for hypothesis generation in future research on barriers to immunization uptake.

KEY WORDS: Immunizations; MMR; public health; GIS; spatial analysis

La traduction du résumé se trouve à la fin de l'article.

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Immunization uptake for preventable illnesses has been a struggle for Canada in the recent past. In 2013, Alberta had 29 measles cases occur in individuals younger than 15 years, and 14 cases occur in individuals aged 15–24. These cases were primarily recorded in Lethbridge, a city with a population just over 90,000, located in the South Health Zone.[1] The source case was exposed to the measles virus from travel to the Netherlands, where a measles outbreak had begun in May 2013.[2] While the outbreak in the South Health Zone ended at the end of 2013, measles outbreaks were declared in the Edmonton, Calgary, and Central Health Zones in April to June 2014. Prior to this, Alberta's most recent outbreaks of an immunization-preventable disease were pertussis outbreaks in 2009 and 2012.[2]

A study by the American Academy of Pediatrics reported that the measles, mumps and rubella (MMR) vaccine is the most frequently refused immunization.[3] Parents who have refused to have their children immunized have cited doing so due to religious, philosophical or personal beliefs. Additionally, some children are not able to receive the immunizations for medical reasons.[4] Recognizing that the entirety of a population may not be immunized or effectively protected by an immunization, herd immunity is a way to extend protection to the unimmunized and unprotected individuals based on the acquired immunity of a large proportion of the population.[5] However, the threshold required to achieve herd immunity through MMR immunization is 95%.[6]

There is a strong geographical component to immunization rates, rates of refusal, and outbreaks. Studies have shown that individuals who choose not to have their children immunized tend to cluster together. These clusters of under-immunized populations also tend to overlap with outbreaks of immunization-preventable illnesses.[4] The relationship between unimmunized clusters and outbreaks was found statistically significant during a pertussis outbreak in Michigan between 1993 and 2004.[7]

Within the literature, many health geography studies use spatial methods, temporal methods, and less commonly spatio-temporal methods. Spatial analyses of the relationship between space and any given phenomena – for example, place and health – as well as temporal analyses assessing how various health conditions change over time are commonplace in the literature.[8] Conversely, spatio-temporal analyses, and particularly analyses of

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how health phenomena change over space and time are much less common. Furthermore, most immunization literature is written from an epidemiological perspective, which typically lacks the integration of geographical concepts. This underutilizes methods that could enhance the information about relationships between immunization rates, time and space.

The objective of this paper is to demonstrate how geospatial analyses can be applied to public health data. This paper will assess how the MMR immunization rates change over space in a given year, how they have changed over time, and what are the space-time interactions of the MMR immunization rates in Alberta.

MATERIALS AND METHODS

Study area

Just under half of the population of Alberta (48%) live in the two metropolitan centres, Calgary and Edmonton, which combined make up only 0.23% of the land area. The rest of the population live in rural areas or urban centres in rural areas. The analyses were conducted for the Health Zone and Local Geographic Areas (LGAs). A summary of these geographic units and their populations can be seen in Table 1.

Data

Alberta Health and Wellness, Surveillance & Assessment Branch collects immunization rate data from four different provincial health databases.[9,10] For this research, two publicly available datasets were used from Alberta Health's Interactive Health Data Application (IHDA).[10] The first dataset contains aggregate immunization records (2004–2008) and is reported for Health Zones (refer to Table 1).[9] The second dataset (2008–2012) consists of individually collected immunization records and is reported for LGAs and Health Zones.[10] These two datasets were combined to create rate data for 2004–2012, seen in Table 2, where individually collected data were used in 2008. Data and limitations will be further addressed in the discussion. The immunization rate is calculated as the ratio between the number of children aged two years and younger who have received their first MMR immunization and the total number of children in that age group.[11]

Table 1. Summary of Alberta's Health Zones

Health zone	Area (sq km)	Percent rural	Number of LGAs	Total population (2012)	Population 2 years and younger
Alberta	663,575	93.6%	132	3,888,634	3.98%
North	451,136	98.2%	43	459,140	4.57%
Edmonton	11,680	0%	35	1,222,278	3.84%
Central	95,459	97.2%	48	458,624	3.86%
Calgary	39,344	90.0%	29	1,455,932	3.93%
South	65,954	74.6%	21	292,491	4.09%

Source: IHDA, 2014.

Analysis

Geographic phenomena tend to display consistent patterns over space. This tendency is well described by Tobler's so-called "first law of geography", which states, "[e]verything is related to everything else, but near things are more related than distant things" (p.236).[12] This well-known statement provides a conceptual framework for geospatial analysis. Within the literature, spatial methods include global indicators of spatial autocorrelation and local indicators of spatial association (LISA). These are all indicators of the degree of spatial autocorrelation, expressing how similar one value is to its neighbouring values.[13] Spatial autocorrelation is measured from negative one, indicating a pattern of perfect dispersion, to positive one, indicating a pattern of perfect clustering. On this scale, zero indicates the lack of any pattern, representing spatial randomness.[8] The difference between global and local methods is that a global indicator is an average of spatial relationships over the whole study area, and cannot indicate the location of spatial association. LISA provides detailed information on the spatial association across the study area, and therefore can identify areas of clustering vs. dispersion. Specifically, Getis and Ord's G* can indicate regions where low values are clustered ($G^* > 0$) and regions where high values are clustered ($G^* < 0$).[14]

In this study, spatial associations were examined only in the individually collected MMR immunization rate data, i.e., between 2008 and 2012, at the LGA level. Spatial analytical tools require the specification of a spatial weights matrix, which defined neighbourhoods of spatial units deemed to be spatially associated.[15] Here, the neighbourhood was defined by "Rook's Case" (an analogy with the chess game) whereby neighbourhoods are formed by LGAs that share a common edge, this being best suited for Alberta's rurality.[15] Global Moran's I assessed the degree of spatial association throughout the province, whereas Getis and Ord's G* assessed localized patterns of spatial association. Statistically significant clusters of high immunization rates and low immunization rates were identified based on first-degree neighbours – that is, in the rook's case, only nearest neighbours sharing a border with the given unit. All spatial analyses were completed in ArcGIS 10.2.

Table 2. Immunization rates for Alberta and Health Zones, 2004–2012

	IHDA aggregated data collection					IHDA individual data collection				
	2004	2005	2006	2007	2008	2008	2009	2010	2011	2012
Alberta	90.27	91.65	91.02	88.52	89.27	89.27	86.83	85.87	85.52	84.26
North	83.64	89.45	87.31	85.54	89.69	85.85	82.58	81.86	82.44	78.21
Edmonton	93.08	90.99	99.37	88.02	92.45	90.01	88.20	87.90	86.98	86.65
Central	88.36	90.22	93.34	86.78	91.07	88.84	86.42	85.87	84.39	81.79
Calgary	93.08	94.80	89.30	91.50	87.77	87.29	84.27	85.71	85.45	84.06
South	90.72	92.51	91.32	89.14	89.42	86.80	86.06	83.61	81.46	78.15

IHDA = Interactive Health Data Application.

Temporal analyses were conducted at the two levels of geographical aggregation, as specified above, resulting in two sets of 6 and 132 time-series analyses. For the five Health Zones, a time series was defined as the immunization rate from 2004–2012, whereas in the LGAs it was defined as completed for 2008–2012. In each time series, immunization rate was regressed over time to determine the coefficient of change per year. Data and model residuals were assessed for homoscedasticity, serial autocorrelation, linearity and normality in R 3.1.2.[13] The rates of change for the 132 LGAs were mapped using ArcGIS 10.2.

These two methods can be combined to assess the spatial nature of the temporal trends exhibited by the data or vice versa.[13] Methods of spatial association were applied to the temporal analysis completed at the LGA level. Using these methods, the spatial association of temporality was examined to assess the space-time interaction of MMR immunization rates.

RESULTS

Temporally the MMR immunization rates fluctuate within each health zone; as well, they exhibit temporal differences across health zones. These fluctuations occur throughout the entire study period, as shown in Figure 1.

In Alberta, the annual rate change was 0.94% ($p = 0.014$) in the Northern Health Zone, 1% ($p = 0.042$) in the Edmonton Health Zone, 0.98% ($p = 0.009$) in the Central Health Zone, 1.31% ($p = 0.0009$) in the Calgary Health Zone, and 1.70% ($p < 0.0001$) in the South Health Zone. Overall Health Zones, the population-weighted immunization uptake decreased at a rate of 1.16% per year. All Health Zones passed all data assumptions, except the Edmonton Health Zone, which failed the test for normality (p-value = 0.027). Log transformations did not significantly change any results, thus, the untransformed data were used. All regressions passed tests on model residuals, except the South Health Zone, which failed the Durbin-Watson test for serial autocorrelation (p-value = 0.03), indicating self-similarity over time.

Figures 2 and 3 compare immunization rates in each LGA in 2008 and 2012. Darker red in the figures indicates higher immunization rates and light colours indicate low immunization rates between 2008 and 2012; many of the LGA have become lighter, indicating decreasing immunization rates over time.

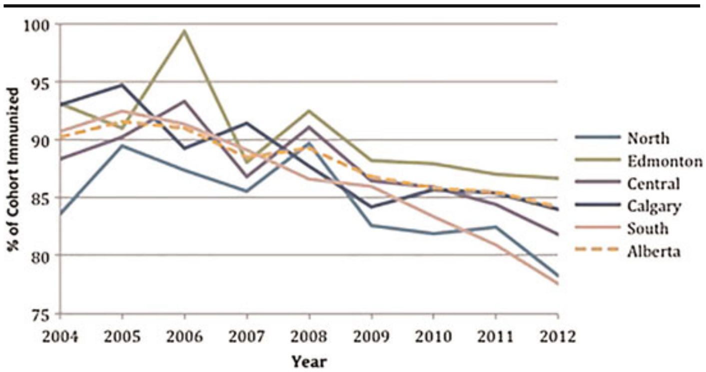

Figure 1. MMR immunization rate trend in Alberta Health regions (solid lines) and the province (dashed line), 2004–2012

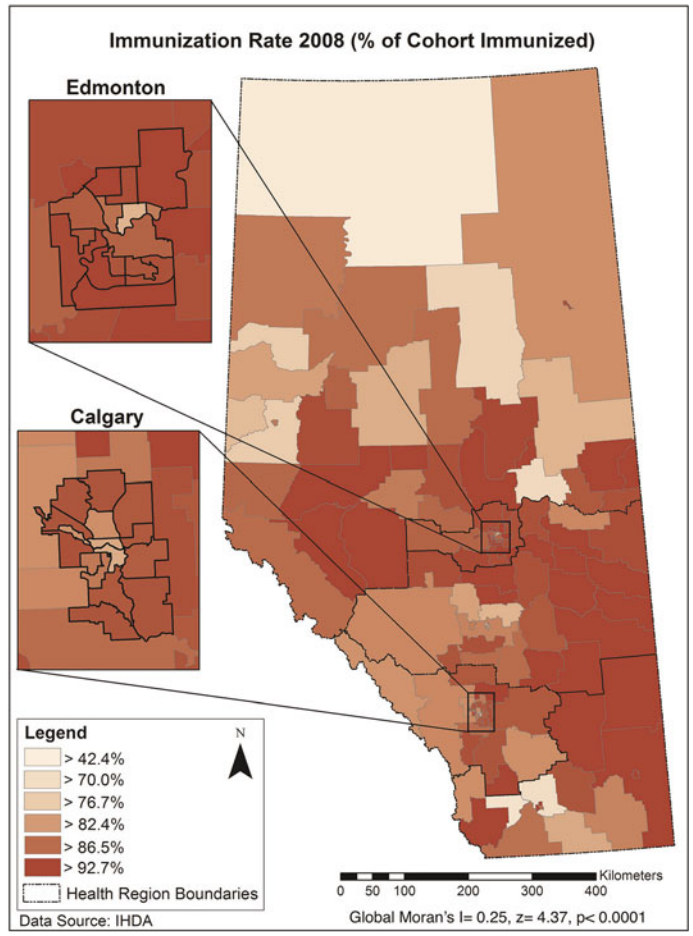

Figure 2. MMR immunization rates, 2008

Only 2.2% ($n = 3$) of LGAs in 2008 have immunization rates that exceeded the immunization coverage required for herd immunity. This decreases to 1.5% ($n = 2$) in 2009, 2010 and 2011, with none of the LGAs achieving herd immunity in 2012.

Figures 4 and 5 show a hot and cold spot analysis that utilizes the Getis and Ord's G* to locate statistically significant clusters of either high immunization rates (represented in red on the map) or low immunization rates (blue on the map). The light yellow indicates LGAs where spatial associations, i.e., local similarities, were statistically insignificant. Between 2008 (Figure 4) and 2012 (Figure 5), the cluster of the low immunization rates in the north expanded, particularly in the east portion. Conversely, clusters of high immunization rates expanded in both metropolitan centres. This is particularly evident in Edmonton, where cold spots are visible in the east and south in 2008 and have expanded to the west and north in 2012. A cluster of high immunization rates appears on the east side of Calgary in 2012. However, the cluster of high immunization rates visible in 2008 east of the corridor between the two metropolitan centres is shrinking in 2012, effectively occurring at a greater distance from the metropolitan centres. The cluster of low immunization rates in the southern part of the province is expanding, both in intensity and spatial extent. Additionally, as the cold clusters expand in 2012, the Global Moran's I increases. This indicates that in Alberta, immunization

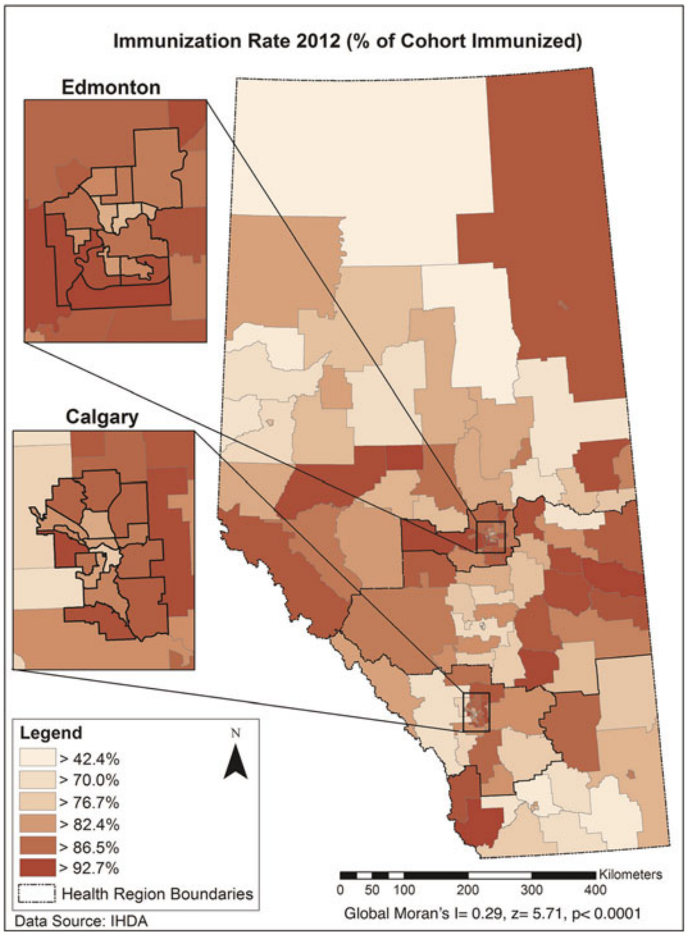

Figure 3. MMR immunization rates, 2012

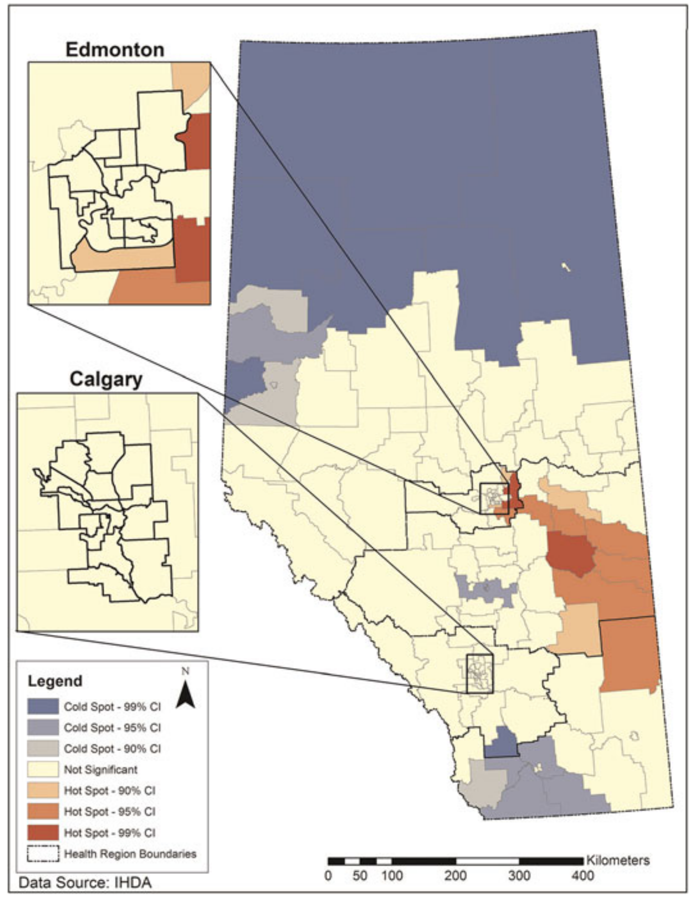

Figure 4. Spatial analysis of immunization rates in 2008
Statistical significance is indicated by the confidence interval (CI).

rates are more spatially autocorrelated, i.e., more self-similar over short distances, in 2012 than in 2008.

The results of spatio-temporal analysis are summarized in Figure 6, which offers a visual representation of trends of immunization rates for each of the 132 LGAs from 2008 through 2012, demonstrating how immunization rates are changing over time in each LGA. Green indicates an increasing immunization rate over time, yellow indicates an immunization rate that is slightly decreasing, light orange indicates a moderate decrease, and dark orange indicates a large decrease in the immunization rate over time. Throughout most of the province, the immunization rates are decreasing. Each health zone has a few LGAs that have increasing immunization rates, except for the South Health Zone where all LGAs have a decreasing immunization rate. The spatial methods can be applied to the temporal analysis above.

The above spatial methods were applied to Figure 6 to produce the results seen in Figure 7. This figure summarizes the interaction between space and time. Unlike the previous maps, this figure shows clusters of increasing or decreasing immunization rates (vs. clusters of high and low rates). The figure shows clusters of decreasing rates in the northwest and southeast corners of the province. Conversely, there are clusters of increasing immunization rates in the two metropolitan centres and west of Calgary. The Global Moran's I shows a slight degree of spatial autocorrelation at a global level. However, when compared to the spatial analysis, the immunization rates are less spatially autocorrelated in space-time than just in space. This indicates that clusters of changing immunization rates are a localized phenomenon, which lacks global homogeneity throughout the province.

DISCUSSION

This research shows that immunization rates are decreasing over most of the province and in many areas immunizations fall short of the 95% herd immunity threshold defined by the Public Health Agency of Canada. The geospatial visualization methods used, such as LISA, can help public health practitioners identify regions of the province that require targeted strategies for increasing immunization rates. More importantly, applying these methods through time makes it possible to show where immunization rates have remained low over a long period or have decreased over time. This analysis gives evidence that the northern region and southern region of the province have the lowest immunization rates both spatially and temporally. Additionally, the research shows that the metropolitan centres of Edmonton and Calgary not only have the highest immunization rates, but also increasing immunization rates over time.

This localized approach can identify areas of local interest and can help identify potential barriers in specific regions, as barriers

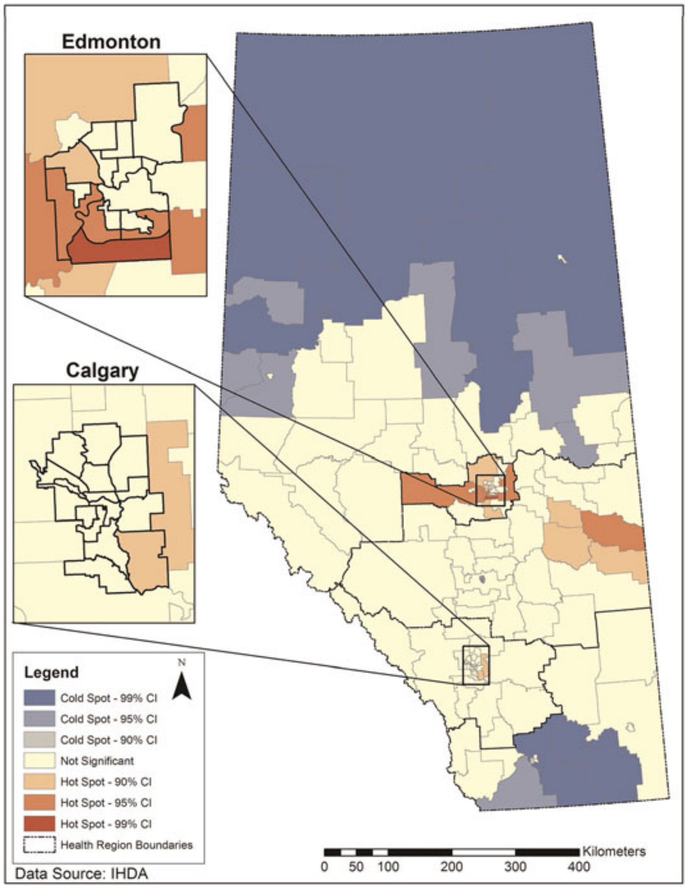

Figure 5. Spatial analysis of immunization rates in 2012

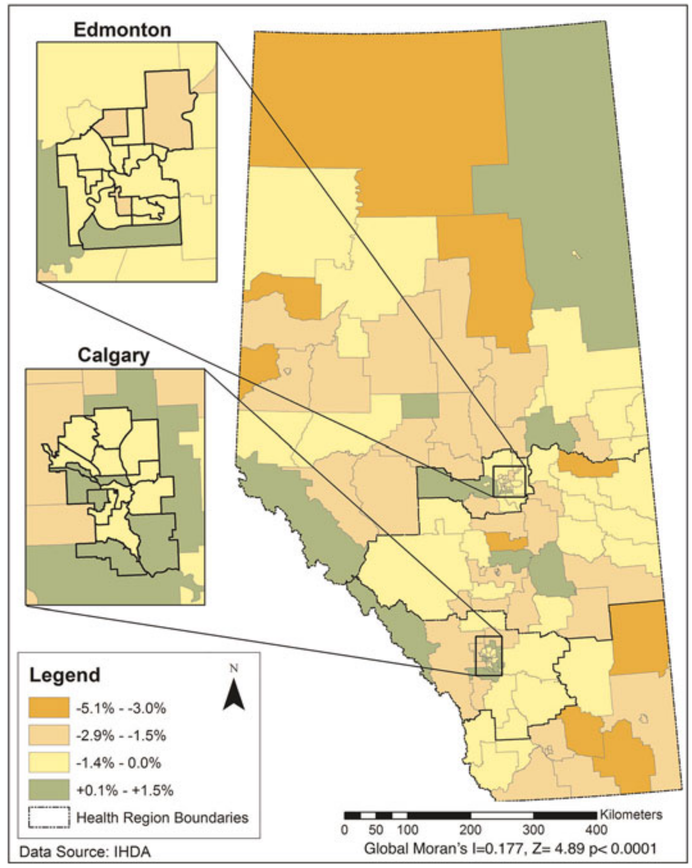

Figure 6. Overall immunization rate changes in each LGA, 2008 through 2012

will likely vary between regions within the province. It is known that barriers to access can play a role in whether or not children receive their immunizations, not only with the MMR immunization but with other routine childhood immunizations. Barriers to access can include the accessibility of clinics and the availability of family doctors, which is recognized in the document "Alberta Immunization Strategy 2007–2017".[16] About 52% of Alberta's population live in areas considered rural or rural remote. This could affect the immunization rates in regions outside the metropolitan centres as there are fewer facilities to service populations spread across geographically large areas.

Religious belief can also play a role in whether or not a child is immunized.[17] Alberta faces specific challenges with meeting the threshold for herd immunity as the southern part of the province has large settlements of groups who generally do not support immunizations, including Hutterites and Netherlands Dutch Reformed Congregations.[18] While not all individuals of these cultures will refuse immunization, they tend to share similar skepticisms around immunizations seen in mainstream society, such as questions about the safety and efficacy of the immunizations.[17] Due to these beliefs, individuals who are part of these communities may also choose to delay immunization of their child or not have their children immunized.[17] Alberta has a high density of these religious groups, predominantly in the southern part of the province.[2] This region also exhibits the lowest immunization rates in the province, the highest spatial and temporal autocorrelation, the largest decline in immunization rate between 2008 and 2012, and the largest decline over space-time. The religious groups in question are known to experience regular outbreaks of immunization-preventable disease, such as pertussis outbreaks every three to five years, a previous measles outbreak in 1997, and a mumps outbreak in 2005.[2,16] Further research is needed to explore and model the relationship between barriers to immunizations in Alberta and immunization rates seen throughout the province, with special attention to different barriers in different regions of the province.

Limitations

While the data come from a reputable source, the research is limited by the available data. During the 2004–2008 reporting period, the IHDA used aggregated immunization reporting datasets, which is advantageous due to timeliness and ease. However, the disadvantage is the potential to over-report immunizations, as it does not take into consideration children who are no longer a part of the reporting population.[9] Additional issues arise from using aggregated data. For example, Lloydminster lies in both Alberta and Saskatchewan and may underestimate the number of children who received immunizations if that child was born in Alberta but received their immunizations in Saskatchewan. Similar issues arise for First Nation children who deviate between on- and off-reserve immunizations.[9] The 2008–2012 dataset is collected at the individual level; therefore, this removes any biases that may be

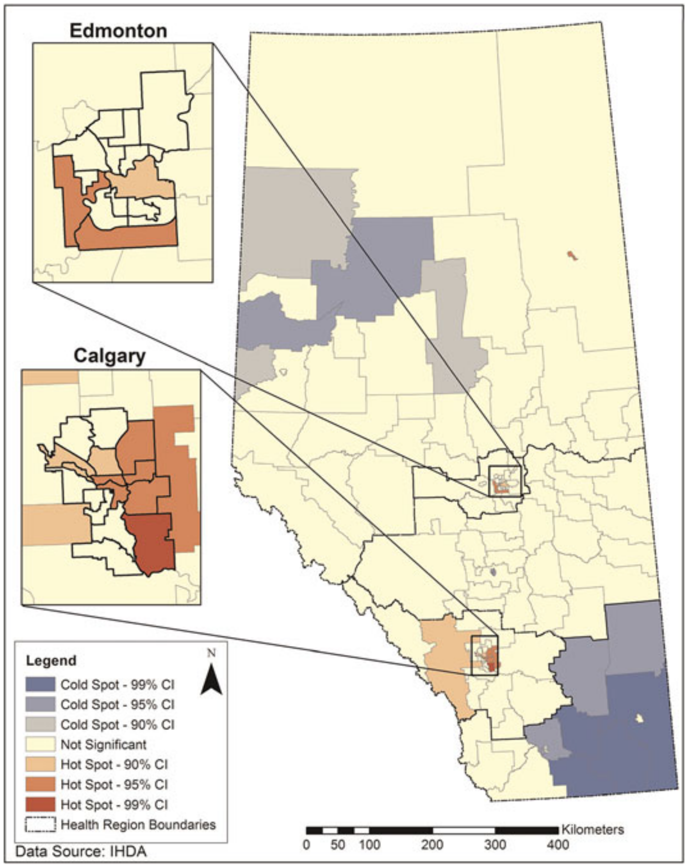

Figure 7. Spatio-temporal analysis of immunization rates in Alberta, 2008 through 2012

present due to the previous data collection method.[10] Figure 2 shows that the aggregate data collection method tends to over-report immunization rates. To date, there has been no assessment of the accuracy or completeness of these datasets.

Other notable issues are the modifiable areal unit problem (MAUP) and the ecological fallacy. With MAUP, analytical results can be affected by the aggregation and scale of analysis. As a result, outcomes can change in response to alterations in the spatial aggregation or boundary delineation.[19] However, the zonation used in this analysis was the finest resolution available, LGA – which was also the geographical unit used for health care planning in Alberta.[11] Additionally, to avoid ecological fallacy, it is important that analytical results not be inferred to other aggregations. For example, results from this analysis cannot be inferred to census geographies or postal geographies.

CONCLUSION

This research demonstrates geospatial applications in epidemiological research. The methods used to assess the spatial, temporal and spatio-temporal trends of MMR immunization rates demonstrate that over space there are clusters of low immunization rates in the north and south of Alberta as well as clusters of higher immunization rates in the metropolitan centres. Over time, the clusters of low immunization rates are expanding, and clusters of high immunization rates are shrinking. Overall, immunization rates are decreasing over most of the province and herd immunity immunization thresholds are not being met throughout Alberta. This puts unprotected individuals at risk of contracting measles, mumps and rubella. Prominent clusters of low immunization rates that occur over space-time can be seen in the northern and southern regions of the province; as well, clusters of high immunization rates in space-time can be seen in the metropolitan centres, Edmonton and Calgary. The patterns shown in this research serve as the basis for hypothesis generation pertaining to the observed patterns.

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RÉSUMÉ

OBJECTIFS : Cette étude évalue la variation temporelle, spatiale et spatio-temporelle des taux de vaccination contre la rougeole, les oreillons et la rubéole (RRO) dans la province de l'Alberta. L'étude utilise les données annuelles des taux de vaccination pour les Zones de Santé et les Zones Géographiques Locales (2004–2012), qui ont été obtenus à partir du « Interactive Health Data Application » du Gouvernement de l'Alberta.

MÉTHODOLOGIES : Les analyses spatiales comprennent une analyse spatiale globale, une analyse « Moran's I » et une analyse d'indicateurs locaux d'association spatiale – Getis et Ord's G* – afin d'identifier des groupes de taux de vaccination élevés ou faibles. Une analyse de séries chronologiques est ensuite appliquée afin d'examiner la façon dont les taux de vaccination changent au fil du temps en collaboration avec leur localisation spatiale.

RÉSULTATS : Les résultats indiquent une baisse des taux de vaccination au fil du temps pour la majorité de la province où la plupart des zones géographiques locales (LGA) tombent à court du seuil de l'immunité grégaire de 95 %. Des groupes de taux de vaccination élevés sont trouvés en centres métropolitains et des groupes de taux faibles sont trouvés en régions du sud et du nord de la province. Ces groupes de taux élevés et faibles existent spatialement et spatio-temporellement. Au fils du temps, les groupes de taux élevés diminuent en taille et les groupes de taux faibles augmentent en taille.

CONCLUSIONS : Cette étude fournit une approche géographique localisé afin d'évaluer les taux de vaccination ROR en Alberta. Les résultats de cette recherche peuvent être utilisés pour cibler les interventions de santé publique à des régions spécifiques qui démontrent les plus faibles taux de vaccination. Ces résultats peuvent également servir d'inspiration pour la génération d'hypothèses d'études futures sur les obstacles liés à l'immunisation.

MOTS CLÉS : immunisations; vaccinations; ROR; santé publique; SIG; analyse spatiale