A multi-dimensional index of rurality in Chile and its association with infant and neonatal mortality

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Flores-Angulo C, Marshall G, Ferreccio C, Ramis R, Gómez-Barroso D, Cerda J. A multi-dimensional index of rurality in Chile and its association with infant and neonatal mortality. Salud Publica Mex. 2026;68:52-61.
https://doi.org/10.21149/17117

Abstract
Objective. To construct a multi-dimensional Index of Relative Rurality (IRR) for Chile and assess its association with infant and neonatal mortality. **Materials and methods.** A cross-sectional analysis was conducted using data from 343 municipalities. The IRR was calculated using four standardized components—population size, population density, urban population proportion, and travel time to service-rich areas—to reflect the complexity of rurality in Chile. Associations between the IRR and mortality outcomes were evaluated using negative binomial regression and generalized additive models. **Results.** A rurality threshold was identified at approximately IRR= 0.404, beyond which the risk of infant and neonatal mortality increased notably. Municipalities with IRR values >0.50 showed elevated risks of infant mortality (RR: 1.18; 95%CI: 1.01,1.38) and neonatal mortality (RR: 1.27; 95%CI: 1.06,1.50), compared to more urban areas. While the official classification defined nearly half of municipalities as rural, the IRR captured a smaller, more specific subset of municipalities with higher mortality risk—particularly in southern macrozones. **Conclusions.** The IRR offers a more precise and data-driven approach to characterizing rurality and identifying health disparities. Its continuous design improves the detection of high-risk populations and challenges the overgeneralization of current classifications. These findings support the use of the IRR to

Flores-Angulo C, Marshall G, Ferreccio C, Ramis R, Gómez-Barroso D, Cerda J. Índice multidimensional de ruralidad en Chile y su asociación con la mortalidad infantil y neonatal. Salud Publica Mex. 2026;68:52-61.
https://doi.org/10.21149/17117

Resumen
Objetivo. Construir un Índice de Ruralidad Relativa (IRR) multidimensional para Chile y evaluar su asociación con la mortalidad infantil y neonatal. **Material y métodos.** Se realizó un análisis transversal utilizando datos de 343 comunas. El IRR se calculó a partir de cuatro componentes estandarizados: tamaño poblacional, densidad poblacional, proporción de población urbana y tiempo de viaje a áreas con alta disponibilidad de servicios, con el fin de reflejar la complejidad de la ruralidad en Chile. Las asociaciones entre el IRR y los desenlaces de mortalidad se evaluaron mediante regresión binomial negativa y modelos aditivos generalizados. **Resultados.** Se identificó un umbral de ruralidad en aproximadamente IRR= 0.404, a partir del cual el riesgo de mortalidad infantil y neonatal aumentó de forma significativa. Las comunas con valores de IRR >0.50 presentaron mayores riesgos de mortalidad infantil (RR: 1.18; IC95%: 1.01,1.38) y neonatal (RR: 1.27; IC95%: 1.06,1.50) en comparación con las zonas más urbanas. Mientras que la clasificación oficial definió como rurales a casi la mitad de las comunas, el IRR identificó un subconjunto más reducido y específico de comunas con mayor riesgo de mortalidad, particularmente en las macrozonas del sur. **Conclusiones.** El IRR ofrece un enfoque más preciso y basado en datos para caracterizar la ruralidad e identificar desigualdades en salud. Su diseño continuo mejora la detección de poblaciones en alto riesgo

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Received on: June 1, 2025 • **Accepted on:** September 5, 2025 • **Published online:** January 14, 2026
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inform targeted public health interventions and equitable policy planning.

Keywords: rurality; infant mortality; neonatal mortality; spatial disparities; Index of Relative Rurality; Chile

y cuestiona la sobregeneralización de las clasificaciones vigentes. Estos hallazgos respaldan el uso del IRR para orientar intervenciones de salud pública focalizadas y la planificación de políticas más equitativas.

Palabras clave: ruralidad; mortalidad infantil; mortalidad neonatal; desigualdades espaciales; Índice de Ruralidad Relativa; Chile

Rurality lacks a universal definition and is commonly characterized by factors such as population density, total population, distance to urban centers, and availability of services.[1] However, its meaning varies across disciplines, leading to inconsistencies in measurement and application.[2-4] From an epidemiological perspective, rurality influences healthcare access, employment opportunities, and social determinants, contributing to disparities in health outcomes.

Rural populations face higher risks of adverse health outcomes, including stillbirth,[5-7] heart failure,[8] and cancer mortality.[9] These disparities stem from limited healthcare access, fewer providers, and greater travel distances,[10-12] compounded by socioeconomic disadvantages such as lower educational attainment and economic constraints.[13-15]

In Chile, rurality has traditionally been defined by the National Rural Development Policy (PNDR), which estimates that 25.5% of the population lives in non-urban areas.[16] Internationally, the framework proposed by the Organization for Economic Co-operation and Development (OECD) also classifies rurality based on fixed thresholds of population density and urban size.[17] However, such dichotomous definitions often fail to capture the territorial complexity and health risk gradients, particularly in geographically diverse countries like Chile.[2,18] In this context, more recent methodological proposals have emerged that incorporate functional and territorial access dimensions, such as the Community Assets and Relative Rurality index, which integrates information on services, amenities, and relative rurality,[2] and the continuous Isolation Measure, which models access to resources based on local population density and travel cost.[19] These tools move toward a multidimensional and continuous conceptualization of rurality, aiming to improve the accuracy of structural inequity assessments.

Chile's vast geographic diversity –spanning over 4 000 km and including remote regions, mountainous areas, and archipelagos– creates substantial disparities in service accessibility and health risks. Many municipalities classified as rural exhibit significant internal variation, highlighting the need for a continuous, data-driven measure of rurality rather than a rigid classification.

This study develops Chile's Index of Relative Rurality (IRR) as a multidimensional measure designed to address the limitations of existing classification systems. By integrating population size, population density, urban proportion, and estimated travel time to areas with a potentially greater availability of services, the IRR provides a more nuanced framework to capture territorial heterogeneity and identify populations that may be at increased risk. This approach strengthens the ability to inform public health policies and support the equitable allocation of resources.

Materials and methods

Study design and data sources

A cross-sectional study was conducted using data from municipalities in continental Chile to examine the association between rurality and infant/neonatal mortality. The rural index was constructed using total population, population density, urban population proportion, and estimated travel time to municipalities with ≥40 000 inhabitants. Its relationship with mortality outcomes was analyzed through statistical models. Infant and neonatal mortality were selected based on evidence linking rurality to disparities in survival,[20] and the methodology was informed by previous multi-dimensional rurality indices.[19] Municipalities, the basic territorial units in Chile, were analyzed considering their geographic, socioeconomic, and demographic characteristics. Demographic and poverty data were obtained from the 2017 Census by the National Statistics Institute (INE) and the Ministry of Social Development and Family.[21,22] Multi-dimensional poverty was assessed across five dimensions: education, health, employment/social security, housing/environment, and social networks/cohesion.[21] Geographic data were obtained from the Ministry of National Assets.[23] Mortality data included 5 487 infant deaths (<1 year) and 4 146 neonatal deaths (<28 days) from 845 567 live births recorded by the INE between 2017 and 2020.[24]

Study area

Chile, located in South America (17°30′ S-56°30′ S), comprises 16 regions and 346 municipalities, which are grouped into five macrozones: North, Center, South-Center, South, and Austral. Of these, 343 municipalities correspond to the mainland territory, which includes both the continental landmass and several inhabited islands that are administratively part of mainland regions, such as Curaco de Vélez, Puqueldón, Quinchao, and Cabo de Hornos. The remaining three municipalities –Easter Island, the Juan Fernández Archipelago, and the Chilean Antarctic Territory– are considered non-mainland due to their insular or polar location.

This study included all 343 mainland municipalities in Chile, using population data from the 2017 Census and complementary administrative sources covering the 2017-2020 period. According to the Office of Agricultural Studies and Policies (ODEPA), municipalities are classified using the OECD territorial grid as predominantly urban (<25% of the population in low-density areas), predominantly rural (>50%), or mixed (25-49%) (OECD, 2010).[16,17] The three non-mainland municipalities were excluded from the analysis due to their geographic isolation, unique demographic structure, and limited comparability with mainland areas. Inclusion criteria required complete data for population size, density, urbanization level, and estimated travel time to ≥40 000 inhabitant localities used as functional references.

Construction of the IRR

The IRR was calculated following Waldorf and Kim using four dimensions: population size, density, urban proportion, and distance to the nearest urban area.[25] Logarithmic transformations were applied to correct skewed distributions. The metropolitan population was defined according to the INE.[22]

Municipalities with ≥40 000 inhabitants were classified as areas with greater service availability.[26] This definition is based on national evidence identifying cities of this size as functional centers where healthcare, education, public administration, and non-agricultural employment are concentrated. These municipalities play a structural role in territorial development and have been shown to contribute to poverty reduction in their surrounding areas.[26] Travel time to these cities was estimated using a Time-Distance Matrix in QGIS,[27] allowing the IRR to incorporate a functional dimension of accessibility. The point layer used to define the origin of each municipality was obtained from the Chilean Spatial Data Infrastructure,[23] representing the location of municipal administrative offices. This choice was based on the premise that these sites approximate the population nucleus more accurately than polygon centroids, which can be spatially misleading in municipalities with large, sparsely populated territories. Instead of relying on Euclidean distance, the matrix computed estimated travel times between municipalities, capturing the actual temporal cost of accessing urban centers and better reflecting the real conditions of geographic connectivity.

To ensure comparability, population size, density, and urban proportion were standardized using equation 1, while distance was adjusted with equation 2 to account for its inverse relationship.

$$X_{jr}escaled=\frac{X_{max}-X_j}{X_{max}-X_{min}} \qquad \text{(equation 1)}$$

$$X_i rescaled=\frac{X_i-X_{min}}{X_{max}-X_{min}} \qquad \text{(equation 2)}$$

The IRR was calculated as the geometric mean of the four dimensions, ranging from 0 (most urban) to 1 (most rural).

$$IRR=(X_{ln(population)} \times X_{ln(density)} \times X_{(\%Urban)} \times X_{Distance})^{1/4} \qquad \text{(equation 3)}$$

For island municipalities administratively part of mainland Chile –such as Curaco de Vélez, Puqueldón, Quinchao, and Cabo de Hornos– travel time was estimated using a combination of land routes and maritime connections to the nearest urban center with a population of at least 40 000 inhabitants. This approach ensured a consistent measure of functional accessibility, accounting for the logistical realities of these territories while maintaining comparability with the rest of the mainland municipalities.

Evaluation of the IRR and statistical analysis

A descriptive analysis of the Chilean population was conducted using IRR and PNDR categories, assessing classification agreement with violin plots. Infant and neonatal mortality were analyzed using total live births as the population base, applying Poisson and negative binomial regression models to address overdispersion. A generalized additive model (GAM) identified the IRR threshold where mortality risk increased, defining rurality categories and estimating overall risk. The geographic distribution of rurality categories was mapped at the municipal level.

No missing data were present in the dataset, as all variables had complete coverage from official sources. Therefore, no imputation methods were required.

All analyses were performed in R, with geospatial visualizations in QGIS. The study was approved by the Ethics Committee of *Pontificia Universidad Católica de Chile* (Project 241015012).

Results

All analyses fitted using negative binomial models to account for overdispersion, included the 343 municipalities of mainland Chile, including Cabo de Hornos, which has the longest estimated travel time to a reference location (~30 hours by land and maritime transport). Although representing an extreme value, sensitivity analyses confirmed that its inclusion did not substantially change the association estimates; therefore, it was kept in all models.

Population characteristics according to the rurality index

Table I presents the distribution of the Chilean population across the ten IRR categories and the three PNDR categories. The IRR ranged from 0 (most urban) to 0.93 (most rural), with a mean of 0.39 and a median of 0.41. Population size decreased progressively with increasing rurality, accompanied by a higher proportion of men and an increased prevalence of multidimensional poverty, particularly in intermediate and high rurality levels. The cartographic representation (figure 1) showed that the most rural areas were concentrated in the southern and austral macrozones of the country.

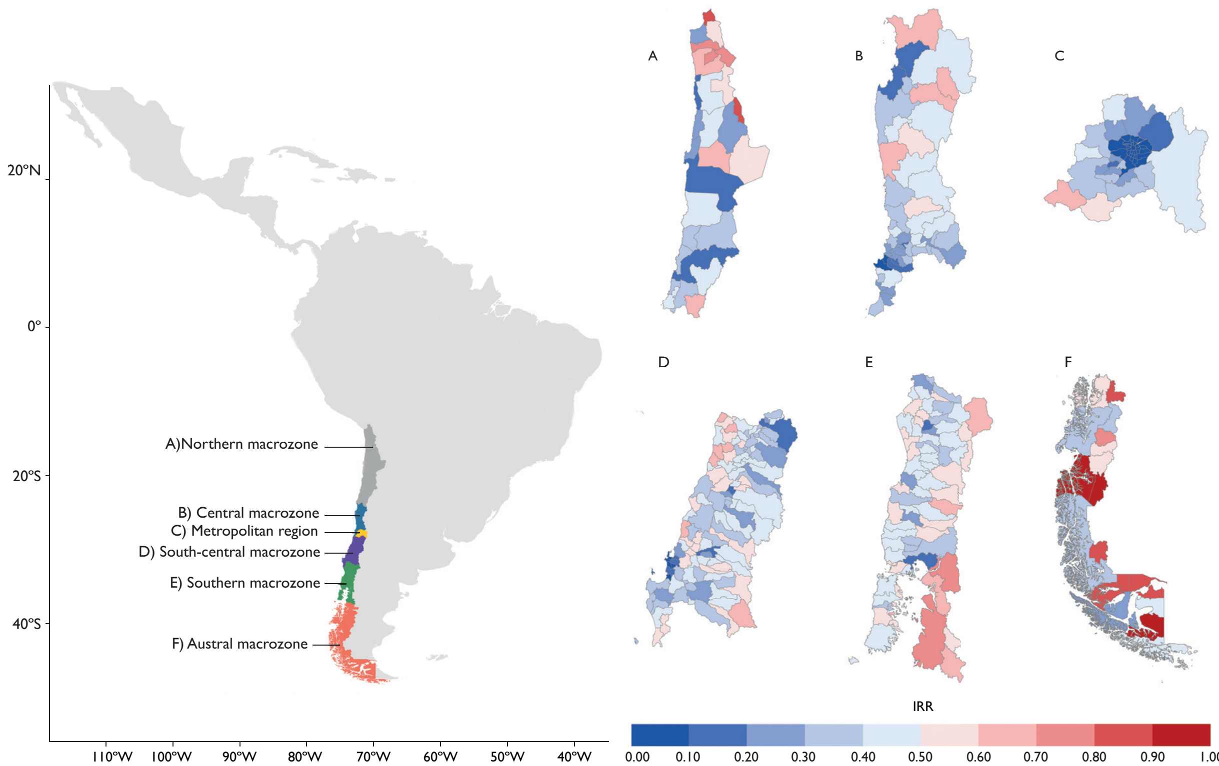
Comparison between the IRR and PNDR classification

Figure 2 shows the distribution of the continuous IRR across the three PNDR groups (urban, mixed, rural). Median IRR values increase from urban to mixed to rural, and the interquartile range shifts upward accordingly. However, the distributions partially overlap: urban municipalities display a right-skewed tail toward higher IRR; mixed municipalities overlap with both urban and rural; and rural municipalities exhibit the highest central tendency but also the widest spread. This pattern indicates broad within-group heterogeneity under the PNDR scheme that the continuous IRR makes visible, while overall trends remain concordant.

Table I
Characteristics of the Chilean population (2017 census) by categories of the IRR and the PNDR

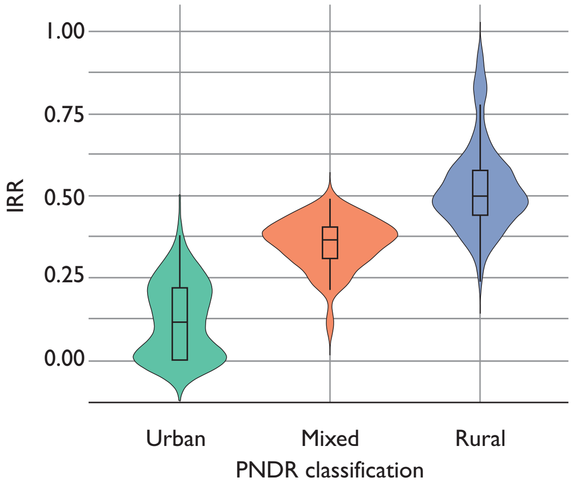
Rurality	*n*	*Population, n(%)*	*Men (%)*	*Pob ≥60 y (%)*	*Poverty, mean*
IRR					
0-0.1	40	7 149 857 (40.70)	48.38	16.17	16.20
>0.1-0.2	20	3 404 176 (19.38)	48.52	14.96	15.39
>0.2-0.3	36	2 794 686 (15.91)	49.18	15.24	17.10
>0.3-0.4	69	2 067 879 (11.77)	49.40	17.06	18.11
>0.4-0.5	88	1 532 362 (8.72)	50.17	18.46	20.54
>0.5-0.6	53	473 448 (2.70)	51.31	19.93	23.88
>0.6-0.7	20	119 321 (0.68)	54.68	20.01	25.02
>0.7-0.8	6	15 993 (0.09)	56.49	19.67	25.94
>0.8-0.9	8	5 914 (0.03)	70.60	15.07	14.23
>0.9-1.0	3	1 553 (0.01)	64.52	10.56	9.28
PNDR					
Urban	82	13 095 911 (74.56)	48.58	15.64	16.15
Mixed	78	2 236 909 (12.73)	49.14	17.39	18.45
Rural	183	2 232 369 (12.71)	50.92	18.44	21.47

Population distribution across 10 Index of Relative Rurality (IRR) categories and 3 National Rural Development Policy (PNDR) categories (urban, mixed, rural). The column "n" indicates the number of municipalities, "Men (%)" the proportion of men, and "Pob ≥60 y (%)" the proportion aged 60 years or older.



A) Northern macrozone; B) Central macrozone; C) Metropolitan region; D) South-central macrozone; E) Southern macrozone; F) Austral macrozone. The color scale represents Index of Relative Rurality (IRR) values: darker blue tones indicate more urban areas (values closer to 0), darker red tones indicate more rural areas (values closer to 1), and lighter shades correspond to intermediate levels of rurality.

Figure 1. Municipal-level distribution of rurality according to the IRR, 2024



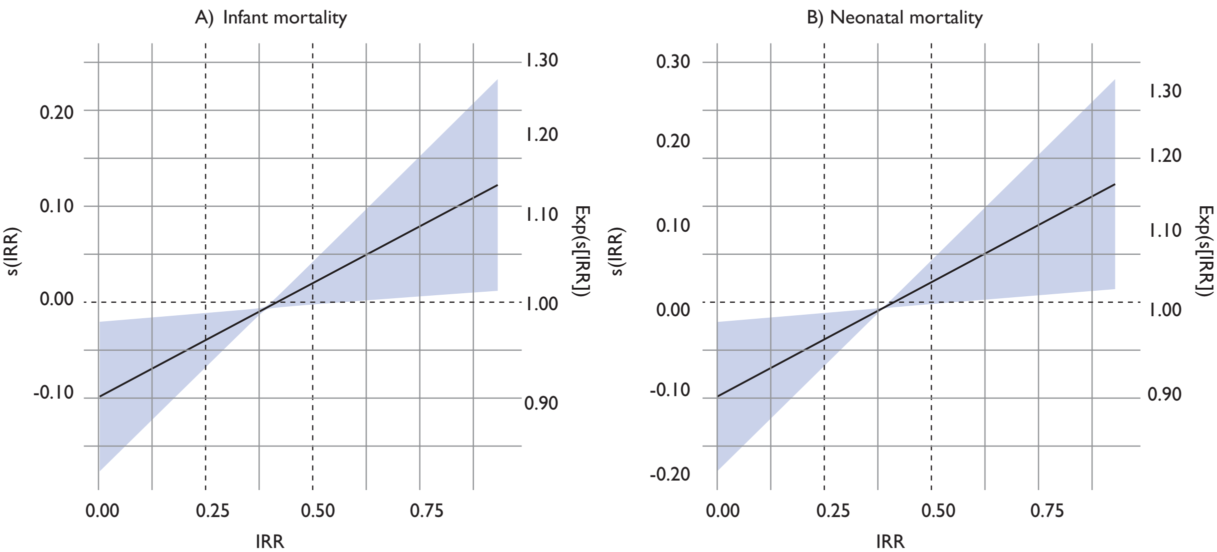
Distribution of Index of Relative Rurality (IRR) values within the urban, mixed, and rural categories according to the National Rural Development Policy (PNDR) classification.

Figure 2. Comparison of the IRR, 2024 and rurality categories of the PNDR, 2020

Generalized additive models and category definition

We modeled the functional association between the continuous IRR and mortality using generalized additive models (negative binomial family with a log offset for live births). The smooth term for IRR showed an upward trend in the partial effect, with an inflection around IRR ≈ 0.404 (figure 3), beyond which the risk increased. To facilitate interpretation and comparison with the PNDR scheme, the continuous IRR was grouped into three analytic categories based on this data-driven threshold: 0-0.25 (lowest rurality), >0.25-0.50 (intermediate rurality), and >0.50 (highest rurality).

When these categories were cross-tabulated with the PNDR classification, the following distribution was observed: among areas classified as rural by the PNDR (*n*= 183), 90 had an IRR >0.50, 92 were in the intermediate category (0.25-0.50), and 1 in the most urban category (<0.25). Among areas classified as urban by the PNDR (*n*= 82), 14.63% had intermediate IRR values.



A) Infant mortality: deaths occurring before one year of age per live births. B) Neonatal mortality: deaths occurring within the first 28 days of life per live births. The figure shows generalized additive model (GAM) plots illustrating the effect of the Index of Relative Rurality (IRR) on mortality.The y-axis displays the partial effect of IRR on a logarithmic scale (left) and an exponential scale (right), with shaded areas indicating 95% confidence intervals.

Figure 3. Impact of rurality on infant and neonatal mortality in Chile (2017-2020): 5 487 deaths, 846 083 live births, 343 municipalities, and a total population of 17.6 million

Association between rurality and infant and neonatal mortality

Negative binomial regression models (table II) showed that areas with an IRR >0.50 had higher risks of infant mortality (RR: 1.18; 95 CI: 1.01,1.38; p= 0.040) and neonatal mortality (RR: 1.27; 95%CI: 1.06,1.50; p= 0.009) compared with less rural areas. In contrast, the PNDR classification did not detect statistically significant differences between rural and urban areas for infant mortality (RR: 1.09; 95%CI: 0.99,1.19; p= 0.076) or neonatal mortality (RR: 1.11; 95%CI: 1.00,1.23; p= 0.059). However, both classification systems showed a progressive increase in mortality risk with increasing rurality.

Discussion

This study developed a composite rurality index for municipalities in mainland Chile and analyzed its association with infant and neonatal mortality between 2017 and 2020. The findings indicate a progressive increase in mortality risk with increasing rurality, with the highest rates observed in municipalities scoring above 0.50 on the IRR. This association reinforces the link between rural residence and adverse early-life health outcomes, particularly in a context shaped by structural inequalities, limited access to services, and geographic isolation.[28-31]

Traditionally, rurality has been defined through a geographic and agrarian lens, based on population density and the size of settlements.[32] In Chile, the PNDR classifies areas with fewer than 150 inhabitants per square kilometer and settlements under 50 000 people as rural.[16] However, this binary approach fails to reflect the current territorial heterogeneity. Literature on "new rurality" has documented transformational processes such as productive diversification, off-farm employment, and growing functional interdependence with urban centers, highlighting the need for more dynamic and multifactorial approaches.[33]

The IRR addresses this need through a continuous measure that incorporates four dimensions: population size, density, urban proportion, and estimated travel time to localities with at least 40 000 inhabitants –used as a functional reference under the assumption of greater service availability–.[26] This structure captures both demographic characteristics and territorial connectivity patterns that influence potential access to services. As a result, the IRR refines the characterization of intermediate territories—traditionally overlooked in dichotomous frameworks—and enables a direct linkage with health outcomes. In this study, the IRR revealed

Table II

Prediction of infant and neonatal mortality in Chile (2017-2020): models based on rurality, population density, and accessibility to services in 343 municipalities and 5 487 deaths

Standardized variables	*Infant mortality*				*Neonatal mortality*			
	AIC	*RR*	*95% CI*	*p*	*AIC*	*RR*	*95% CI*	*p*
1. Population (*n*= 17 565 189)	1 659.4	1.23	0.96,1.57	0.101	1 547.5	1.26	0.95,1.66	0.105
2. Urban (*n*= 15 416 941)	1 660.4	1.13	0.94,1.34	0.192	1 547.2	1.19	0.97,1.46	0.083
3. Density	1 659.2	1.18	0.97,1.43	0.090	1 548.2	1.17	0.94,1.45	0.163
4. Time travel	1 654.1	1.36	1.10,1.69	0.004	1 545.0	1.33	1.04,1.70	0.021
IRR	1 656.8	1.27	1.04,1.56	0.020	1 544.8	1.32	1.04,1.66	0.020
IRR 0-0.25 (*n*= 79)	1 659.5	Ref.			1 545.2	Ref.		
IRR >0.25-0.50 (n= 174)		1.04	0.97,1.12	0.280		1.05	0.96,1.15	0.256
IRR >0.50 (*n*= 90)		1.18	1.01,1.38	0.040		1.27	1.06,1.50	0.009
PNDR (n) [density, inh/km^2]								
Urban (*n*= 82) [100.69]	1 660.9	Ref.			1 548.6	Ref.		
Mixed (*n*=78) [35.70]		1.03	0.94,1.13	0.552		1.02	092,1.14	0.687
Rural (n= 183) [3.99]		1.09	0.99,1.19	0.076		1.11	1.00,1.23	0.059

Index of Relative Rurality (IRR) ranges from 0 (most urban) to 1 (most rural, equivalent to 100%), calculated as the geometric mean of four standardized variables categorized by their impact on mortality. The National Rural Development Policy (PNDR) classifies municipalities by population density. Infant mortality refers to deaths occurring before one year of age per 1 000 live births, and neonatal mortality to deaths before 28 days per 1 000 live births. AIC (Akaike Information Criterion) is used to compare model fit, with lower values indicating better performance. RR: risk ratio; CI: confidence interval; P: *p*-value for the variable in the model.

significant gradients of risk that went undetected by the official PNDR classification. Only half of the most rural municipalities identified by the IRR matched those labeled rural under the PNDR definition, suggesting a misclassification that may hinder the effective targeting of health interventions.

We evaluated the IRR's performance against two critical outcomes representing different stages of early life: infant and neonatal mortality. Infant mortality is shaped by household conditions, community environment, and sustained access to healthcare, while neonatal mortality depends more directly on immediate perinatal care and local health infrastructure.[34,35] The stronger and statistically significant association between rurality and neonatal mortality suggests that the IRR is especially sensitive to timely access barriers. This finding supports its applicability in other epidemiological contexts where access and timeliness are decisive—such as acute illnesses, maternal health, cancer care, and decompensated chronic conditions.[36-38]

Internationally, instruments like Codes of Rural-Urban Commuting Area (RUCA) and Codes of Frontier and Remote Area (FAR) have sought to overcome the limitations of binary classifications by incorporating functional criteria, though they still rely on categorical frameworks.[39,40] In contrast, the IRR aligns with a methodological shift toward continuous, adaptable, and locally informed measures. Its use has demonstrated advantages in public health research in the United States, particularly in studies on risk behaviors such as tobacco use.[41] In Latin America, the Economic Commission for Latin America and the Caribbean (ECLAC) has promoted the development of similar indices in countries like Mexico and Panama.[42-44] In Chile, regional or connectivity-based proposals have emerged,[45,46] yet none have been empirically linked to health outcomes. This study helps fill that gap by demonstrating the IRR's usefulness for mapping child health risks.

Beyond its analytical value, the IRR has important operational implications. Since it relies on publicly available demographic and geospatial data, the index is replicable, updatable, and transferable to other settings. Policymakers can integrate it into epidemiological monitoring systems, territorial planning tools, and resource allocation frameworks, thus supporting a more territorially responsive health policy. In countries with persistent health disparities and diverse rural landscapes, the IRR offers a practical way to better identify vulnerable populations and optimize public health responses.

Limitations

Though widely accepted, the IRR faces criticisms regarding variable weighting and conceptual oversimplification,[47] which we addressed by assigning equal importance to four rurality-related dimensions. Nonetheless, the index has limitations. While municipalities with over 40 000 inhabitants are generally assumed to have broader service availability, this study did not examine the actual presence or type of services provided in those areas. Moreover, the absence of longitudinal data restricts the assessment of temporal changes in service provision, meaning that some highly populated areas may still lack adequate infrastructure. The IRR also relies on estimated car travel times, excluding other transport modes, and combines 2017 census data with spatial measures from 2024, which may introduce inconsistencies. Future census updates and detailed service-level datasets will be crucial to improve the IRR's precision and its relevance for rural health policy.

Conclusions

This study developed the IRR for most Chilean municipalities, offering a more precise tool to assess the impact. The results showed that the most rural group consistently exhibited the highest risk of infant and neonatal mortality, underscoring the IRR's capacity to capture gradients of disadvantage not detected by traditional classifications. By refining how rurality is measured, the IRR contributes to a deeper understanding of territorial inequities and can inform public health surveillance, epidemiologic research, and the spatial targeting of health interventions. Its continuous and multidimensional nature makes it particularly valuable for identifying vulnerable populations and guiding equitable policy responses in geographically diverse settings.

Funding

This project was funded by the National Agency for Research and Development of Chile (ANID) through the Doctoral Scholarship Program(Exempt Resolution No. 1690/2022) and the FONDAP Program (Grant No. 152220002).

Declaration of conflict of interests. The authors declare that they have no conflict of interests.

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