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Spatiotemporal patterns of mortality from stroke and acute myocardial infarction in Ecuador (2018-2024) and their relationship with critical care infrastructure and specialized personnel: a nationwide ecological study

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Abstract

Background. Stroke and acute myocardial infarction (AMI) are leading causes of mortality in Ecuador. Whether their geographic distribution constitutes true statistical clusters, and whether such clusters relate to critical care infrastructure and specialized personnel, has not been formally tested.

Methods. Spatial and longitudinal ecological study, 221 cantons, RECORD framework, integrating the General Mortality Registry, the Hospital Beds and Discharges Registry, the Health Resources and Activities Registry, and INEC population projections, 2018–2024. Global and local (LISA) spatial autocorrelation were tested, and mixed-effects negative binomial panel models estimated the association between cluster membership and mortality, adjusting for year, ICU beds, and (2018–2021 subsample) cardiovascular/neurological staffing.

Results. AMI community mortality rose markedly after 2019 without returning to prior levels; stroke showed no significant temporal trend. Moran's index confirmed significant spatial autocorrelation for both conditions (AMI: $I = 0.466$; stroke: $I = 0.216$; both $p < 0.001$). LISA identified a 29-canton high-risk cluster for AMI in Guayas, Manabí, and Los Ríos, including Guayaquil. Cluster membership was associated with higher mortality for AMI (IRR 2.85, 95%CI 2.14–3.80) and stroke (IRR 2.25, 95%CI 1.59–3.20), independent of year. Neither ICU bed availability, cardiovascular/neurological specialized staffing, nor cantonal poverty (Unsatisfied Basic Needs, NBI) explained this association: NBI was inversely and significantly associated with mortality (likely reflecting under-ascertainment in high-poverty, largely Amazonian cantons), and the cluster association strengthened after adjustment (AMI: IRR 3.22; stroke: IRR 2.31). In-hospital mortality rate declined steadily for both conditions (AMI: 13.9%→9.66%; stroke: 14.8%→11.2%), alongside an expansion of national ICU bed supply (1,050→1,330).

Conclusions. Stroke and AMI mortality in Ecuador show a concentrated, statistically robust territorial pattern that was not associated with differences in critical care infrastructure or specialized personnel across cantons. This points to the need to investigate additional territorial determinants —cardiovascular risk factor burden, timeliness of access, diagnostic certification quality— rather than hospital resource distribution alone. Mortality was consistently higher in men, with the largest sex gap in young adults, attenuating with age.

BACKGROUND

Cardiovascular diseases are the leading cause of death worldwide. According to the 2021 Global Burden of Disease (GBD) study, ischemic stroke affected 7.8 million people that year and remains the second leading cause of death and the third leading cause of disability globally (1), and the most recent GBD estimates for cardiovascular disease as a whole confirm that stroke and ischemic heart disease —including acute myocardial infarction (AMI)— remain among the leading causes of disability-adjusted life years in virtually every region of the world (2). In Latin America and the Caribbean, accelerated urbanization, population aging, and persistent socioeconomic inequality configure a cardiometabolic risk landscape with marked heterogeneity both between and within countries (3). Spatial epidemiology

studies in large Latin American cities have consistently documented spatial autocorrelation in cardiovascular mortality —geographic clustering not attributable to chance— partly explained by the spatial distribution of socioeconomic disadvantage (4), and recent multicenter work analyzing hundreds of Latin American cities has found that within-city variability in cardiovascular mortality exceeds between-city or between-country variability, underscoring that fine-scale territorial inequalities are frequently more determinant than national average differences (5).

Ecuador has not been exempt from this epidemiological transition, and presents an additional challenge documented by prior studies: the distribution of critical care capacity in the country has historically been heterogeneous, with marked concentration in major urban centers (6). Stroke and AMI also share a clinical feature critical to health service organization: both are time-dependent conditions, in which the interval between symptom onset and access to definitive care —thrombolysis or endovascular intervention for stroke, coronary reperfusion for AMI— largely determines clinical outcome, making physical distance and critical infrastructure availability plausible determinants of observed mortality in a country with Ecuador's geographic and population dispersion. Prior ecological studies on stroke morbidity and mortality in Ecuador have described differential geographic risk patterns by altitude and province of residence, with follow-up series of up to 17 years (7), and analogous work on traumatic brain injury has documented territorial heterogeneity associated with behavioral risk factors and road infrastructure (8). However, none of these studies has applied formal tests of spatial autocorrelation — global Moran's index and local indicators of spatial association (LISA)— to determine whether the observed geographic patterns constitute statistically significant clusters, nor has any quantitatively evaluated whether such clusters, if present, are associated with differences in the availability of critical infrastructure and specialized medical personnel between territories, or whether they reflect other determinants not captured by these variables.

This study aims to characterize the spatiotemporal behavior of stroke and AMI mortality in Ecuador during 2018–2024, to formally identify and quantify geographic risk clusters through spatial autocorrelation analysis, and to evaluate —through a mixed-effects panel model incorporating indicators of critical capacity and specialized personnel— whether these clusters are associated with patient-external differences in health resource availability, or whether they point to the need to investigate additional territorial determinants.

METHODS

2.1 Design and data sources

Spatial and longitudinal ecological study, 2018–2024, RECORD framework (9). Sources: General Mortality Registry (community mortality, n = 7 complete years), Hospital Beds and Discharges Registry (11) (morbidity, mortality rate, and installed capacity, n = 6–7 years depending on variable), and INEC Population Estimates and Projections by canton, sex, and five-year age group. Cartography: official

CONALI-CNE 2022 cantonal boundaries, projected coordinate reference system EPSG:32717 (WGS 84 / UTM zone 17S).

2.2 Operational definitions

Stroke: ICD-10 I60, I61, I63, I64. I62 (other nontraumatic intracranial hemorrhage, including chronic subdural hemorrhage) was deliberately excluded from the stroke case definition, consistent with prior population-based studies of stroke mortality in Ecuador (7), given its distinct clinical course and etiologic heterogeneity relative to acute stroke subtypes. AMI: ICD-10 I21-I22 (primary definition). Canton of residence was determined using the "cant_fall" variable in the General Mortality Registry, restricted to records flagged as resident ("residente"=1) at the canton of death registration, which we used as a proxy for canton of usual residence; this approach follows INEC's own coding convention and was adopted specifically to reduce transfer bias, since non-resident decedents (e.g., patients who died after being transferred to a referral hospital outside their home canton) are excluded by this filter. Nonetheless, some residual transfer bias cannot be ruled out for cantons hosting major referral hospitals, an issue addressed through the sensitivity analysis described in section 2.7 below. In hospital discharge records, canton of residence was determined directly through the "cant_res" variable.

2.3 Standardization and in-hospital mortality rate

Crude and age-sex-adjusted mortality rates (direct standardization, annual national reference) were calculated for each canton-year. In-hospital mortality rate was calculated according to the official INEC definition (in-hospital deaths / total discharges × 1,000), distinguishing early (< 48 h) from late (≥ 48 h) death.

2.4 Spatial analysis

A queen-contiguity neighborhood matrix was constructed for the 218 continental cantons (Galápagos province excluded due to geographic discontinuity), with row-standardized spatial weights. Global Moran's index was calculated on the 2018–2024 adjusted average rate for each condition, using analytical (asymptotic) significance testing under randomization, as implemented in the spdep R package. The local indicator of spatial association (LISA) was used to identify specific clusters (high-high, low-low, and outliers), with per-canton significance set at the conventional $p < 0.05$ threshold and without correction for multiple comparisons across the 218 spatial units tested, following common practice in the applied LISA literature; this choice is acknowledged as a limitation, since it increases the likelihood of some false-positive cluster assignments at the level of individual cantons, and the cluster boundaries reported (section 3.4) should be interpreted as a description of the dominant spatial pattern rather than as a set of individually validated significance tests.

2.5 Panel model

A mixed-effects negative binomial model (random intercept by canton, log-population offset) was fitted to the complete canton-year panel (n = 1,526, 218 cantons × 7 years), with year centered at 2018 and an indicator variable for LISA risk-cluster membership as fixed predictors. Nested models (null, with trend,

with cluster) were compared using Akaike's information criterion (AIC), and goodness of fit was assessed through simulated residual diagnostics (DHARMa). Because the risk-cluster indicator was derived from the same 2018–2024 average mortality rates used as the outcome in this model, the resulting incidence rate ratio should be interpreted as a measure of the internal consistency and magnitude of the spatial pattern already identified by LISA, rather than as an independent, out-of-sample validation of that pattern; this distinction is discussed further in section 2.6.

2.6 Declared methodological limitations

- Ecological design: does not permit individual-level causal inference.
- Circularity in the spatial-panel sequence: the LISA risk cluster was defined using the same 2018–2024 average mortality rates subsequently modeled as the outcome in the panel model (section 2.5), rather than validated on an independent, out-of-sample period. This means the reported cluster incidence rate ratio quantifies the internal consistency and magnitude of an already-identified spatial pattern rather than providing independent predictive validation. A temporally split design (e.g., defining clusters using 2018–2020 data and modeling 2021–2024 outcomes) would address this limitation directly but was not pursued here, as halving the observation window was judged likely to compromise the statistical power needed to detect clusters reliably, particularly for stroke, given the small-area case-count instability documented in the pilot phase of this project. This trade-off is acknowledged explicitly as an unresolved methodological limitation rather than treated as a resolved issue.
- Geographic distance to critical capacity not included in the final model: exploratory analysis of geographic accessibility using centroid-to-centroid Euclidean distance showed a weak, counterintuitive negative correlation with mortality (2018 cross-section; Supplementary Material S2), most likely reflecting small-area case-count instability and under-ascertainment in remote cantons rather than a genuine protective effect of distance, and was therefore not incorporated into the panel model. Ecuador's Comprehensive Health Care Model (MAIS-MSP) defines official accessibility through road-network isochrones (30–360 minutes depending on rurality) (10); replacing Euclidean distance with actual travel time remains a pending methodological extension.
- Cantonal poverty (NBI, 2022 Census) was incorporated as a cross-sectional predictor (section 3.8), but rurality and population density were not; these remain unincorporated territorial confounders.
- ICU bed supply reflects normed capacity, not real-time operational availability.
- Certification of AMI as cause of death showed a low autopsy-confirmation rate (verified in the 2018 subset), which limits the diagnostic specificity of the primary definition.
- The binary cluster-membership predictor, while capturing the main risk contrast identified by LISA, does not fully account for spatial dependence: Moran's I on model residuals remained substantial for both conditions (AMI: $I = 0.455$; stroke: $I = 0.211$; both $p < 0.001$; Supplementary Material S3), concentrated predominantly in the Amazon region and likely reflecting systematic under-ascertainment there rather than an unmodeled risk factor within the identified clusters. A continuous spatial structure (e.g., conditional autoregressive or spatial lag terms) explicitly

modeling this residual dependence was not implemented in this analysis; given the magnitude of residual autocorrelation observed, this is considered a substantive limitation rather than a minor caveat, and represents the most important direction for future methodological extension of this work.

2.7 Sensitivity analyses

To address possible residual transfer bias associated with major referral hospitals, the main panel model was re-estimated excluding cantons hosting the largest national referral centers (Guayaquil and Quito), and results were compared with those from the full sample. Spatial autocorrelation of model residuals was additionally assessed via Moran's I on the residuals of the main panel model to evaluate whether meaningful spatial structure remained unaccounted for after including cluster membership as a predictor. Results of both sensitivity analyses are presented in the Supplementary Material.

2.8 Statistical software

All statistical analyses were performed in R (version 4.6.1; R Foundation for Statistical Computing, Vienna, Austria). Spatial data management and choropleth mapping used the sf and ggplot2 packages; spatial neighborhood matrices and global/local indicators of spatial association (Moran's I, LISA) were computed with the spdep package; mixed-effects negative binomial panel models were fitted using glmmTMB, and goodness-of-fit was assessed through simulated residual diagnostics with the DHARMa package. A two-sided p-value < 0.05 was considered statistically significant throughout.

2.9 Use of AI-assisted technology

A large language model (Claude, Anthropic) was used during manuscript preparation to assist with drafting and editing text, formatting tables and figure captions, and organizing revisions in response to methodological feedback. The AI tool was not used to design the study, perform statistical analyses, generate or fabricate data or results, or produce scientific interpretations independent of author oversight; all statistical analyses were performed directly by the authors in R as described in section 2.8, and all data, code, results, and interpretations were reviewed, verified, and are the sole responsibility of the authors. The AI tool is not listed as an author or contributor, consistent with the journal's authorship criteria.

RESULTS

3.1 Community mortality, 2018–2024 panel

Between 1,875 (2020) and 2,723 (2021) annual deaths from stroke were recorded, and between 6,853 (2018) and 13,306 (2024) from AMI. AMI mortality increased markedly after 2019, without returning to previous levels, reaching a historical maximum in 2024. Stroke mortality showed no consistent temporal trend over the period (Table 1).

Table 1
Annual mortality from stroke and AMI among residents, Ecuador 2018–2024.

Year	Stroke deaths	AMI deaths
2018	2,246	6,853
2019	2,283	7,493
2020	1,875	12,742
2021	2,723	11,663
2022	2,528	12,178
2023	2,289	12,167
2024	2,421	13,306

AMI, acute myocardial infarction. Source: INEC, General Mortality Registry.

3.2 In-hospital mortality rate and intensive care capacity

In-hospital mortality rate declined steadily for both conditions between 2018 and 2024 (stroke: 14.8%→11.2%; AMI: 13.9%→9.66%), with the sharpest decline in 2023–2024. In parallel, the national ICU bed supply increased from 1,050 (2019, the series minimum) to 1,330 (2024, historical maximum) (Table 2).

Table 2
In-hospital mortality rate and intensive care capacity, Ecuador 2018–2024.

Year	Stroke mortality rate	AMI mortality rate	National ICU beds	Cantons with ICU
2018	14.8%	13.9%	1,183	33
2019	14.2%	11.9%	1,050	32
2020	15.1%	12.5%	1,135	29
2021	14.5%	13.2%	1,256	31
2022	13.3%	11.9%	1,239	30
2023	12.6%	9.82%	1,289	31
2024	11.2%	9.66%	1,330	31

AMI, acute myocardial infarction; ICU, intensive care unit. Source: INEC, Hospital Beds and Discharges Registry.

The national ICU bed supply remained, throughout the series, well below the Ministry of Public Health standard (0.5 high-complexity beds per 1,000 population, equivalent to ~ 50/100,000 population) (10); in

2018, the national rate was 6.93 ICU beds per 100,000 population, 14% of the regulatory target.

In addition to ICU bed supply, two indicators of specialized personnel and infrastructure were characterized, available from the Health Resources and Activities Registry (RAS-INEC) for 2018–2021: cardiovascular response staffing (cardiac and cardiovascular surgeons, intensivists, intensive care units, and cardio-resuscitation carts per canton) and neurological response staffing (neurologists, neurosurgeons, intensivists, and intensive care units per canton). Together, these three indicators —ICU beds, cardiovascular response staffing, and neurological response staffing— constitute the characterization of patient-external infrastructure and personnel evaluated in sections 3.6 and 3.7 as a possible determinant of the identified risk clusters (Table 3).

Table 3
Patient-external specialized infrastructure and personnel, Ecuador.

Indicator	What it includes	National total 2018	National total 2021	Cantons with supply (2021)
ICU beds	Normed supply of intensive care beds	1,183	1,256	31 / 221
Cardiovascular response staffing	Cardiac/cardiovascular surgeons, intensivists, ICUs, cardio-resuscitation carts	1,712	1,975	100 / 221 (2018)
Neurological response staffing	Neurologists, neurosurgeons, intensivists, ICUs	1,312	1,551	69 / 221 (2018)

ICU, intensive care unit; RAS-INEC, Health Resources and Activities Registry (Instituto Nacional de Estadística y Censos). ICU beds: Hospital Beds Registry 2018–2024 (INEC). Cardiovascular and neurological response staffing: RAS-INEC 2018–2021. Values represent the sum of supply reported per canton and do not represent a count of unique individuals.

3.3 Spatial autocorrelation: Moran's index

Global Moran's index confirmed positive and significant spatial autocorrelation for both conditions on the 2018–2024 adjusted average rate: AMI ($I = 0.466$; $z = 11.04$; $p < 0.001$) showed markedly stronger spatial clustering than stroke ($I = 0.216$; $z = 5.22$; $p < 0.001$).

3.4 LISA clusters

LISA analysis identified a high-high cluster of 29 cantons for AMI (13.3% of the 218 continental cantons), contiguously concentrated in the provinces of Guayas (16 cantons), Manabí (7), and Los Ríos (5), and including Guayaquil, the country's most populous city (Fig. 1). For stroke, the high-high cluster comprised 12 cantons distributed across three geographically discontinuous cores: northern Manabí, Bolívar, and southern Azuay (Fig. 2).

LISA, local indicators of spatial association. Galápagos province excluded (geographic discontinuity). Source: INEC 2018–2024 — author's elaboration.

3.5 Mixed-effects panel model

The mixed-effects negative binomial model showed substantial improvement in fit upon incorporating LISA cluster membership (ΔAIC AMI: -393.5; ΔAIC stroke: -17.5 relative to the model with temporal trend alone). In both models, simulated residual dispersion testing showed no evidence of residual overdispersion (AMI: p = 0.456; stroke: p = 0.872).

Table 4
Incidence rate ratio (IRR) from the mixed-effects negative binomial panel model, controlling for canton.

Condition	Predictor	IRR	95% CI	p value
AMI	Year (per year)	1.137	1.123–1.151	< 0.001
AMI	Risk cluster	2.851	2.137–3.803	< 0.001
Stroke	Year (per year)	1.011	0.997–1.026	0.135
Stroke	Risk cluster	2.254	1.586–3.203	< 0.001

AMI, acute myocardial infarction; IRR, incidence rate ratio; CI, confidence interval.

Risk-cluster membership was independently associated with mortality risk for both conditions, with a larger effect size and narrower confidence interval for AMI (as noted in section 2.5, this association reflects the internal consistency of the spatial pattern already identified by LISA on the same data, not an independent out-of-sample test). The annual temporal trend was significant only for AMI. A sensitivity analysis excluding the two cantons hosting the country's largest referral hospitals (Guayaquil, Quito) yielded a virtually unchanged cluster association for AMI (IRR 2.84, 95%CI 2.12–3.81, vs. 2.85, 95%CI 2.14–3.80 in the full sample; Supplementary Material S1), indicating that the cluster association is not driven by transfer-related bias toward major referral centers.

3.6 Is the cluster explained by a deficit in intensive care capacity?

To evaluate whether higher mortality within the cluster was driven by lower availability of critical resources, the proportion of cantons with ICU bed supply was compared inside and outside the AMI risk cluster. Contrary to the hypothesis of a simple infrastructure deficit, 17.2% of cluster cantons (5 of 29) had some ICU bed supply, a proportion similar to —and even slightly higher than— that observed outside the cluster (13.8%, 26 of 189). Notably, the cluster includes Guayaquil, the canton with the country's largest installed intensive care capacity (416 beds in 2024), which nonetheless shows a significantly elevated AMI mortality rate relative to the rest of the national territory (Table 5).

Table 5
Selected cantons within the AMI risk cluster by mortality rate and ICU bed supply, 2024.

Canton	Province	Average AMI rate /100,000	ICU beds (2024)
Jipijapa	Manabí	187.8	0
Pedro Carbo	Guayas	179.7	0
Salitre	Guayas	167.8	0
Paján	Manabí	157.4	0
Guayaquil	Guayas	105.5	416
Portoviejo	Manabí	61.7	82

AMI, acute myocardial infarction; ICU, intensive care unit. The coexistence of cantons with no supply at all (Jipijapa, Pedro Carbo) alongside the country's highest-capacity canton (Guayaquil) within the same cluster suggests that ICU availability was not the primary factor associated with the excess territorial risk.

This finding indicates that the excess territorial risk is not simply explained by the availability of critical infrastructure, and points to the need to investigate other territorial determinants —prevalence of cardiovascular risk factors, patterns of timely access to care, quality of diagnostic certification, or other structural factors— that this ecological design cannot directly discriminate, given the absence of sources with cantonal representativeness for individual clinical variables (hypertension, diabetes, obesity, smoking), which in Ecuador have sample representativeness only at the provincial level (ENSANUT) (13).

3.7 Sensitivity model: specialized infrastructure and personnel (2018–2021)

To formally evaluate whether the observed cluster effect is explained by differences in specialized infrastructure and personnel, cardiovascular response staffing (cardiac and cardiovascular surgeons, intensivists, intensive care units, and cardio-resuscitation carts) and neurological response staffing (neurologists, neurosurgeons, intensivists, intensive care units) were constructed from the Health Resources and Activities Registry (RAS-INEC), available only for 2018–2021. Both indicators, expressed per 100,000 population, were incorporated as additional predictors in a panel model restricted to that period (Table 6; n = 872, 218 cantons × 4 years).

Table 6
Sensitivity panel model (2018–2021) incorporating specialized infrastructure and personnel (RAS-INEC).

Condition	Predictor	IRR	95% CI	p value
AMI	Year (per year)	1.281	1.246–1.317	< 0.001
AMI	Risk cluster	3.176	2.337–4.317	< 0.001
AMI	Cardiovascular staffing /100k	1.006	0.994–1.019	0.322
Stroke	Year (per year)	1.091	1.052–1.132	< 0.001
Stroke	Risk cluster	2.291	1.603–3.275	< 0.001
Stroke	Neurological staffing /100k	1.016	0.998–1.035	0.082

*AMI, acute myocardial infarction; IRR, incidence rate ratio; CI, confidence interval; RAS-INEC, Health Resources and Activities Registry. The risk-cluster effect remains robust and of similar or greater magnitude than in the main model (*Table 4*) after controlling for specialized infrastructure and personnel, while the latter does not reach statistical significance for either condition.*

Incorporating specialized infrastructure and personnel did not improve model fit relative to the version without this variable, evaluated on the same period and sample (ΔAIC AMI: +1.0). This comparison is restricted to models fitted on the identical 2018–2021 sample and is not directly comparable to the AIC values reported for the main 7-year model (Table 4), which was fitted on a different period and sample size. Within this restricted comparison, cardiovascular and neurological staffing were not statistically associated with mortality, while the cluster effect remained robust; this pattern does not support the hypothesis that the territorial inequality in cardiovascular mortality identified through LISA is explained by differences in the availability of specialists or cardiovascular/neurological critical infrastructure between cantons, though it cannot be considered definitive proof of absence of any such relationship given the ecological design and restricted time window.

As a further refinement specific to stroke, cantonal availability of emergency computed tomography (CT) —the diagnostic study required to distinguish ischemic from hemorrhagic stroke and guide acute treatment decisions— was evaluated as an additional binary predictor (any emergency CT performed in the canton-year vs. none), separately from the continuous neurological staffing index to avoid conflating counts of personnel/infrastructure with counts of performed procedures. CT availability was not significantly associated with stroke mortality (IRR 1.17, 95%CI 0.91–1.49, p = 0.215), and the cluster association remained essentially unchanged (IRR 2.28, 95%CI 1.60–3.24). No equivalent emergency procedure-based refinement was available for AMI, since the RAS registry does not capture percutaneous coronary intervention or catheterization capacity (section 2.6).

3.8 Sensitivity model: territorial poverty (Unsatisfied Basic Needs)

To evaluate whether the risk-cluster association reflected an underlying territorial poverty gradient, the percentage of the population classified as poor by Unsatisfied Basic Needs (Necesidades Básicas Insatisfechas, NBI; 2022 Population and Housing Census) was incorporated as an additional predictor in the main 7-year panel model (Table 7; n = 1,526, 218 cantons × 7 years, identical sample to Table 4).

Table 7
Panel model incorporating cantonal poverty (NBI, 2022 Census) as a predictor.

Condition	Predictor	IRR	95% CI	p value
AMI	Year (per year)	1.137	1.123–1.151	< 0.001
AMI	Risk cluster	3.217	2.416–4.284	< 0.001
AMI	NBI (%, cantonal)	0.989	0.984–0.994	< 0.001
Stroke	Year (per year)	1.011	0.996–1.026	0.138
Stroke	Risk cluster	2.309	1.649–3.234	< 0.001
Stroke	NBI (%, cantonal)	0.990	0.985–0.994	< 0.001

AMI, acute myocardial infarction; IRR, incidence rate ratio; CI, confidence interval; NBI, Unsatisfied Basic Needs poverty index. Source: INEC, 2022 Population and Housing Census.

Contrary to the hypothesis that greater territorial poverty would be associated with higher cardiovascular mortality, cantonal NBI was significantly and inversely associated with mortality for both conditions (AMI: IRR 0.989 per percentage point, 95%CI 0.984–0.994; stroke: IRR 0.990, 95%CI 0.985–0.994), and its inclusion improved model fit relative to the version without it (ΔAIC AMI: -14.1; ΔAIC stroke: -17.2, both evaluated on the identical 7-year sample as Table 4). This counterintuitive direction is consistent with the pattern already identified in sections 3.6 and Supplementary Material S2-S3: cantons with the highest NBI poverty are concentrated predominantly in the Amazon region, the same region identified as most affected by probable case under-ascertainment, so the inverse association is more plausibly explained by differential diagnostic ascertainment than by a genuine protective effect of poverty. Critically, the risk-cluster association remained robust, and its magnitude increased rather than decreased after adjusting for NBI (AMI: IRR 3.22 vs. 2.85 unadjusted; stroke: IRR 2.31 vs. 2.25 unadjusted), indicating that the territorial inequality identified through LISA is not explained by cantonal poverty as measured by NBI, and if anything becomes more pronounced once poverty is accounted for.

3.9 In-hospital mortality rate by age group

Analysis of in-hospital AMI mortality rate by five-year age group, over the complete 2018–2024 series (n = 24,778), showed a non-monotonic pattern: relatively elevated mortality rate in young adults (25–29 years: 17.9%), a minimum between 40 and 59 years (5.4–5.9%), and a sustained increase from age 65 onward up to a maximum of 31.8% in those over 85. The age group concentrating the largest proportion

of cases (55–74 years, 38.9% of the total) is located precisely within the range of lowest relative mortality rate (Fig. 3).

AMI, acute myocardial infarction. Bars represent the percentage distribution of cases; line represents in-hospital mortality rate (%). Source: INEC, Hospital Beds and Discharges Registry — author's elaboration.

3.10 Galápagos province: complementary analysis

The three cantons of Galápagos province (San Cristóbal, Isabela, Santa Cruz) were excluded from spatial autocorrelation tests (Moran's index, LISA) due to geographic discontinuity with the continental territory, a structural limitation of the contiguity method used. They are presented descriptively and independently: during 2018–2024, 34 deaths from AMI were recorded (27 in Santa Cruz, 7 in San Cristóbal, none in Isabela) and 7 from stroke across the province. The low case volume, even accumulated over the seven-year series, does not permit reliable estimation of temporal trends or adjusted cantonal rates for this province; it is reported as complementary information, without direct comparison to the continental pattern.

3.11 Sex and age differences and provincial distribution

AMI mortality was consistently higher in men than in women across all age groups analyzed (2018–2024), with the sex gap largest in young adults (20–29 years: RR 3.4, 95%CI 2.7–4.3) and narrowing progressively with age (> 85 years: RR 1.18, 95%CI 1.16–1.21). The sex gap for stroke was systematically smaller and, unlike AMI, was not statistically significant in three age groups (15–19, 45–49, and 85 and over), consistent with a less pronounced sex differentiation for stroke than for AMI. Aggregation at the provincial level confirmed the pattern identified through cantonal-level LISA, with Guayas, Los Ríos, and Manabí showing the highest AMI mortality rates nationally; provincial aggregation, however, partially disperses the finer territorial signal captured at the cantonal level, and is presented here only as complementary context to the primary cantonal-level evidence (Supplementary Material S4-S6).

DISCUSSION

The central finding of this study is the identification of a robust, statistically quantified territorial pattern in AMI and stroke mortality in Ecuador, one that remained significant even after adjusting for the most plausible patient-external variables: ICU bed availability, cardiovascular response staffing, and neurological response staffing. None of these three variables was statistically associated with mortality within the panel model, and the cluster effect remained similar or even increased upon their inclusion. This finding does not support the simplest and most intuitive hypothesis ("fewer hospitals, more deaths") and instead calls for interpreting the finding in terms of territorial health inequality: the geographic coincidence of elevated mortality with the presence of critical infrastructure —Guayaquil itself, with the country's largest installed capacity, lies within the risk cluster— suggests that the problem may not be one of resource availability alone, but potentially one of population-level cardiovascular risk factor burden, the timing and quality of access to that care, or referral and triage processes that this ecological design does not directly capture. Given the ecological, cross-sectional nature of the

infrastructure indicators (2018–2021 only) and the observational design overall, these findings should be interpreted as associations rather than causal statements.

Extending this analysis to cantonal poverty (section 3.8) did not change this interpretation, but added an important nuance. Contrary to what a straightforward socioeconomic determination hypothesis would predict, cantonal NBI poverty was inversely associated with mortality for both conditions, and the cluster association strengthened rather than weakened after this adjustment. Taken together with the negative correlation between distance to critical care and mortality (Supplementary Material S2) and the concentration of residual spatial autocorrelation in the Amazon region (Supplementary Material S3), the most parsimonious explanation for this counterintuitive direction is differential case ascertainment: the Amazon region, which combines the highest NBI poverty, the greatest distances to critical care, and the lowest recorded cardiovascular mortality nationally, is the most plausible site of systematic underreporting, rather than a region of genuinely lower cardiovascular risk. This interpretation is offered as the most parsimonious explanation consistent with the available evidence, not as a demonstrated mechanism; distinguishing true regional risk variation from differential ascertainment would require primary data collection (e.g., verbal autopsy studies or targeted surveillance) in the Amazon region, which lies beyond the scope of this registry-based analysis.

Several alternative or complementary mechanisms cannot be excluded with the available data. First, competing risks from other causes of death (infectious, maternal, perinatal, or violent) may curtail life expectancy in high-poverty cantons before cardiovascular disease typically manifests, reducing recorded cardiovascular mortality without implying lower underlying cardiovascular risk. Second, residual transfer bias in the direction opposite to that addressed in section 2.7 —critically ill patients from remote, high-poverty cantons transferred to referral hospitals elsewhere and recorded as deaths in the receiving canton— could artificially deflate rates in cantons of origin and inflate them elsewhere. Third, small-area statistical instability in sparsely populated Amazonian cantons, even after seven years of accumulated data, may still produce unstable rate estimates for some units. Finally, a genuine difference in underlying cardiovascular risk between rural Amazonian and urbanized coastal populations —differences in diet, physical activity, and exposure to the cardiometabolic risk profile associated with urbanization (3)— remains a biologically plausible alternative that this ecological, registry-based design cannot rule out. Regardless of which of these mechanisms, alone or in combination, best explains this specific counterintuitive finding, its presence across three independent analyses (distance, poverty, and residual autocorrelation) does not undermine the central and consistently replicated finding of this study: the Costa risk cluster identified through LISA is robust across every specification tested, including adjustment for critical care infrastructure, specialized personnel, and cantonal poverty.

This study also contributes three elements not previously documented for Ecuador. First, it confirms through formal statistical testing —not merely descriptive observation— the existence of a geographic AMI mortality cluster spanning nearly the entire south-central Coast region of the country, with an almost threefold risk relative to the rest of the territory, independent of year.

Second, the dissociation between temporal trend (significant only for AMI) and cluster effect (significant for both conditions, though of differing magnitude) suggests that stroke and AMI respond to partially distinct causal processes in Ecuador: AMI appears to be driven both by a stable territorial component and by a sustained temporal shock —consistent with the impact of the COVID-19 pandemic on cardiovascular mortality. A national cross-sectional analysis of Ecuadorian registry data for 2019–2020 similarly reported a marked rise in total AMI deaths alongside a stable in-hospital mortality rate among hospitalized patients, with the large majority of deaths occurring outside the hospital setting in both years (12) —a pattern consistent with the interpretation, developed further below, that the excess mortality observed nationally reflects prehospital rather than in-hospital determinants. Stroke, in contrast, shows a predominantly territorial pattern, with no clear temporal trend.

Third, the sustained improvement in in-hospital mortality rate alongside rising community AMI mortality —particularly marked in 2020–2021— is more consistent with a problem of prehospital access and timeliness than with deterioration in the quality of in-hospital care, though this remains a plausible hypothesis rather than a directly tested finding, since this study did not measure transfer times, prehospital delay, or emergency medical service response. Patients who reached hospital care did not show worse outcomes during the period; the excess mortality observed at the population level probably occurred, in a proportion not quantifiable with these data, outside the hospital system. This interpretation is consistent with broader evidence that prehospital emergency care systems in low- and middle-income countries, including Latin America, remain comparatively underdeveloped and that delays in time-to-reperfusion for AMI disproportionately affect rural and geographically dispersed populations (14, 15).

These findings have direct public health policy implications: the magnitude of the cluster effect (IRR 2.25–2.85) places the Guayas-Manabí-Los Ríos region as an objectively quantified territorial priority for strengthening cardiovascular resolutive capacity, while the persistent gap relative to the national ICU bed standard (actual supply equivalent to only a fraction of the MAIS-MSP target throughout the series) signals a structural limitation of the system that the pandemic failed to reverse proportionally to need.

CONCLUSIONS

There is a robust spatial cluster, statistically validated through Moran's index and LISA, of AMI mortality in south-central coastal Ecuador, with a relative risk close to three times that of the rest of the country, quantified independently of temporal trend through a mixed-effects panel model. In-hospital mortality rate improved steadily during 2018–2024 for both conditions, suggesting that public health interventions should prioritize prehospital access and response over in-hospital care quality, which already shows a trajectory of improvement. ICU bed supply remains well below the official standard of the Ecuadorian health system throughout the entire period analyzed.

Abbreviations

AMI, acute myocardial infarction; CI, confidence interval; CT, computed tomography; DHARMa, R package for simulated residual diagnostics; ICD-10, International Classification of Diseases, 10th revision; ICU, intensive care unit; INEC, Instituto Nacional de Estadística y Censos (Ecuador's National Institute of Statistics and Census); IRR, incidence rate ratio; LISA, local indicators of spatial association; MAIS-MSP, Modelo de Atención Integral de Salud, Ministerio de Salud Pública (Ecuador's Comprehensive Health Care Model, Ministry of Public Health); NBI, Necesidades Básicas Insatisfechas (Unsatisfied Basic Needs poverty index); RAS-INEC, Registro de Recursos y Actividades de Salud (Health Resources and Activities Registry); RECORD, REporting of studies Conducted using Observational Routinely-collected Data; RR, relative risk.

Declarations

Ethics approval and consent to participate

This study used exclusively secondary, de-identified, aggregate administrative data from routinely collected public national registries (General Mortality Registry, Hospital Beds and Discharges Registry, Health Resources and Activities Registry, and national census/population data), all published by Ecuador's National Institute of Statistics and Census (INEC). No individual-level or identifiable patient data were accessed, and no direct interaction with human participants occurred. Institutional ethics committee approval was therefore not required for this analysis, consistent with national and institutional policy for research based on publicly available, aggregate, de-identified administrative data.

Consent for publication

Not applicable. This manuscript does not contain any individual person's data in any form.

Availability of data and materials

The datasets analyzed during the current study are publicly available from the Instituto Nacional de Estadística y Censos (INEC) of Ecuador. The General Mortality Registry and Hospital Beds and Discharges Registry are available at https://www.ecuadorencifras.gob.ec/; the 2022 Population and Housing Census poverty (NBI) data are available at https://www.ecuadorencifras.gob.ec/pobreza-por-necesidades-basicas-insatisfechas/. The Health Resources and Activities Registry (RAS-INEC) is available upon request to INEC. Cantonal boundary shapefiles are available from CONALI-CNE (2022). The consolidated cantonal-year dataset, analysis code, and derived outputs generated during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

ASHA conceived and designed the study, curated and analyzed the data, performed the statistical and spatial analyses, and drafted the manuscript. ESLM supervised the project, contributed to interpretation of the findings, critically revised the manuscript for important intellectual content, and served as corresponding author. AWGV and AATS contributed to study conception and methodological guidance and critically revised the manuscript. MGS contributed to the clinical interpretation of the findings and critically revised the manuscript. LGP contributed to data interpretation and critically revised the manuscript. All authors read and approved the final manuscript.

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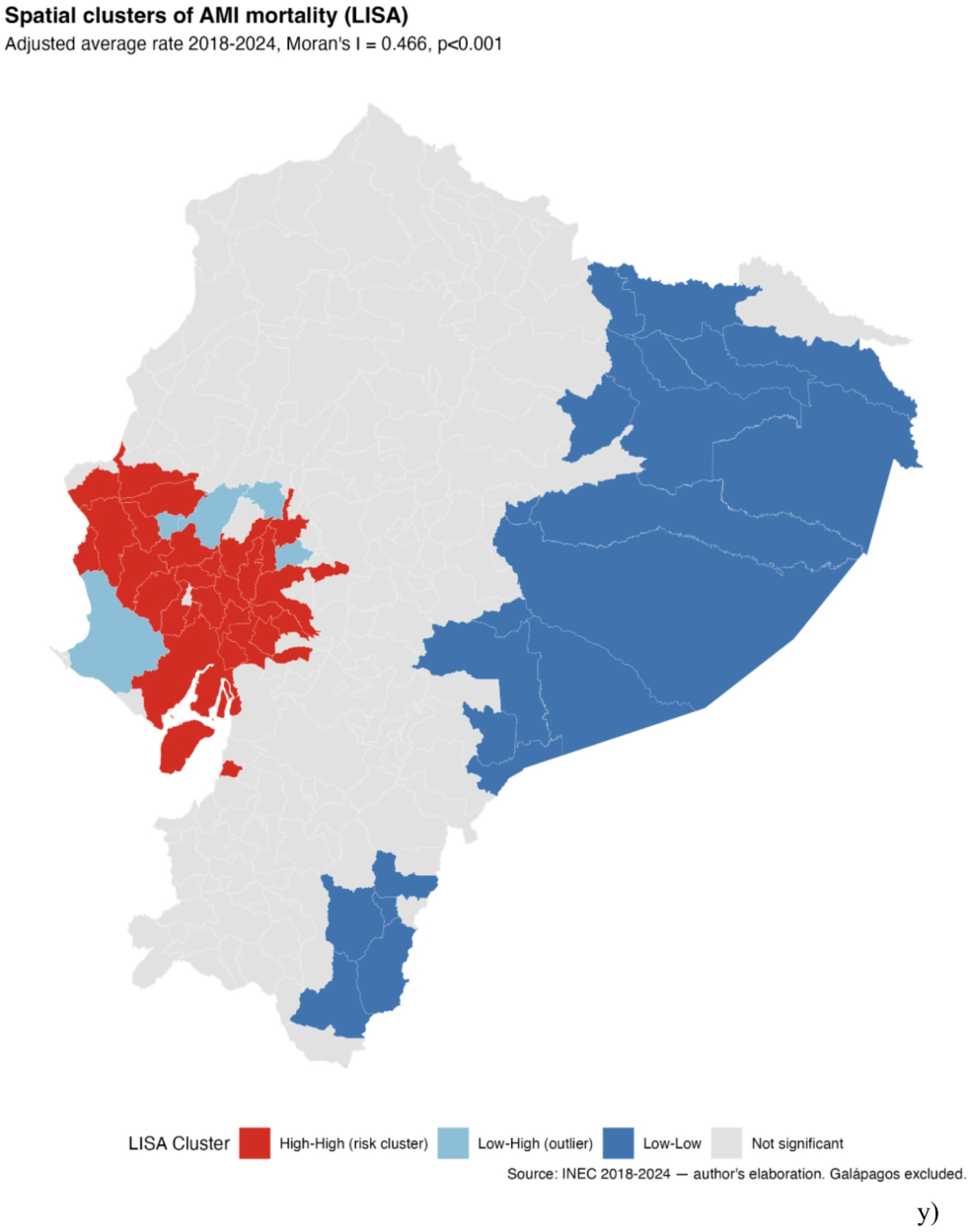
Not applicable.

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Figures



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Figure 1

LISA spatial clusters of AMI mortality, adjusted average rate 2018-2024.

AMI, acute myocardial infarction; LISA, local indicators of spatial association. Galápagos province excluded (geographic discontinuity). Source: INEC 2018-2024 — author's elaboration.

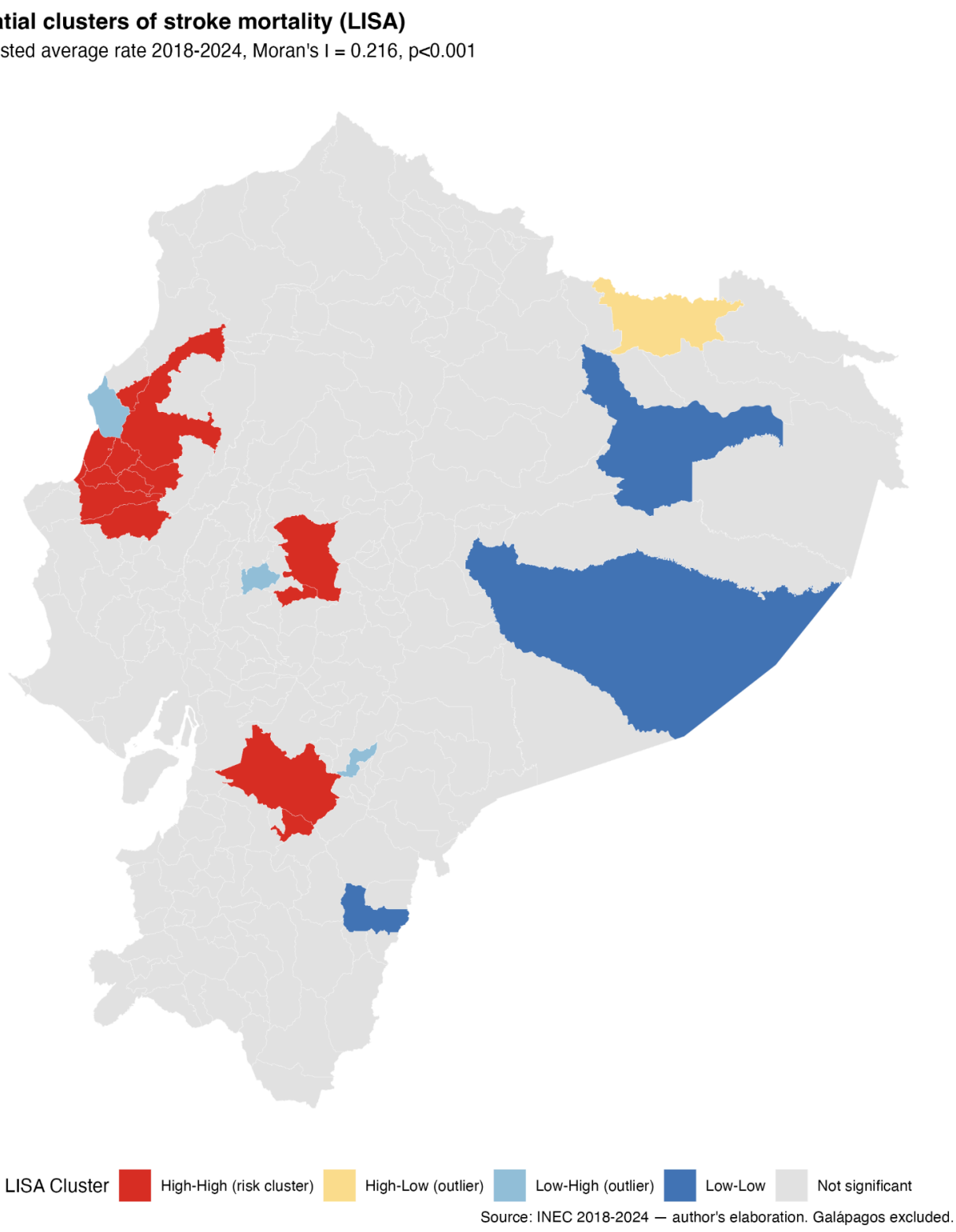


Figure 2

LISA spatial clusters of stroke mortality, adjusted average rate 2018-2024.

LISA, local indicators of spatial association. Galápagos province excluded (geographic discontinuity). Source: INEC 2018-2024 — author's elaboration.

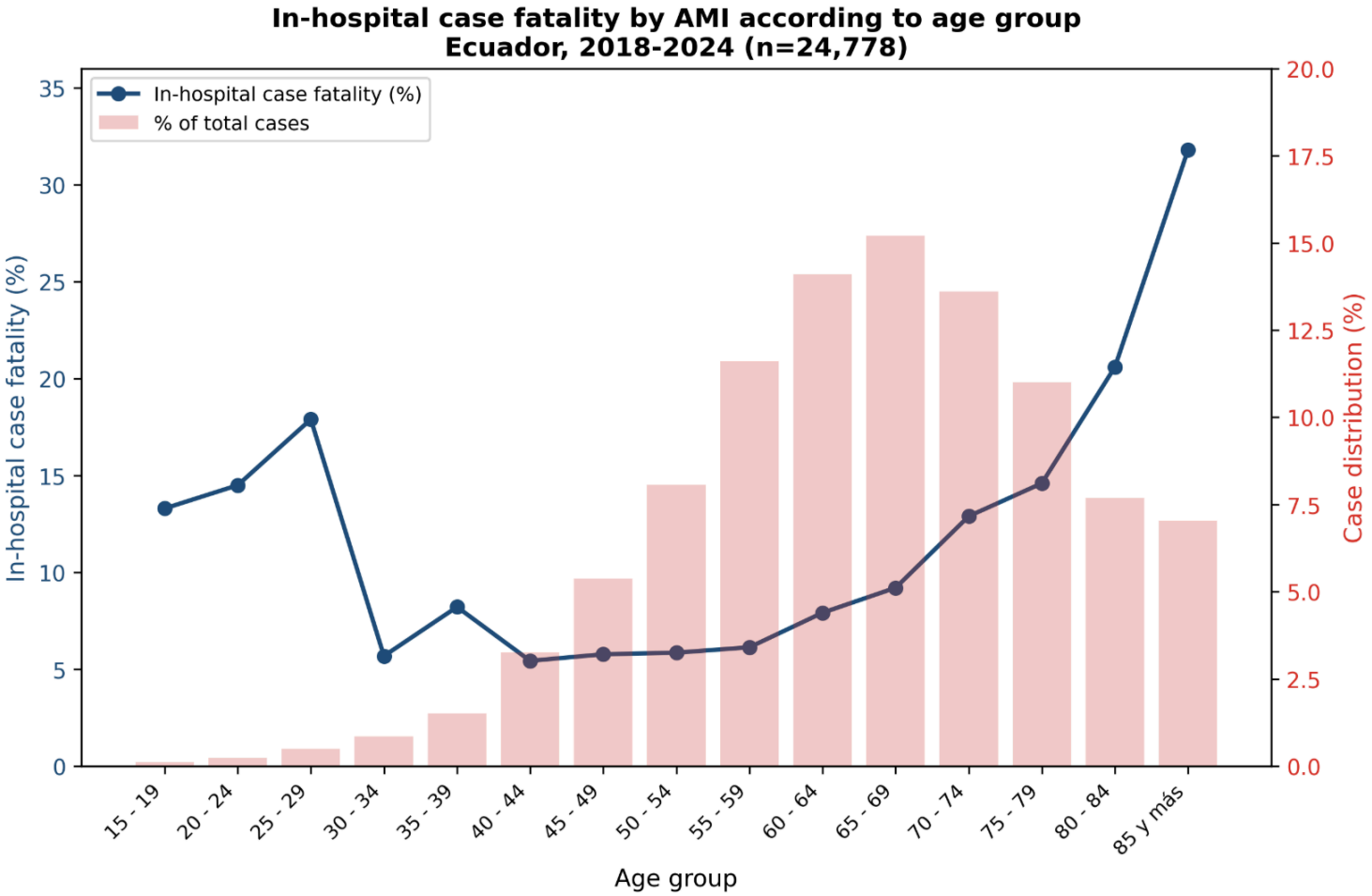


Figure 3

In-hospital mortality rate from AMI by five-year age group, Ecuador 2018-2024 (n=24,778).

AMI, acute myocardial infarction. Bars represent the percentage distribution of cases; line represents in-hospital mortality rate (%). Source: INEC, Hospital Beds and Discharges Registry — author's elaboration.

Supplementary Files

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