Full Title

The role of climate services for health: Theoretical case studies on heat-health warning systems in India

Short Title

Climate services and heat-health in India

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Abstract

Extreme heat is a growing public health concern across South Asia, with urban populations particularly vulnerable due to high population density, infrastructure gaps, and compounding socioeconomic risks. In this study, we assess the potential health benefits of Heat–Health Warning Systems (HHWS) as a Climate Service for Health (CSH) in urban India and explore their role in enhancing public health interventions in the context of rising heat exposure. We focus on two key outcomes—heat-related all-cause mortality and preterm birth—and estimate the potential impact of HHWS over the 2025–2035 period using a theoretical modelling framework adapted from Mistry et al.

Our model considers three scenarios: no intervention, a baseline public health intervention (Heat Action Plans or Atosiban administration), and an enhanced intervention enabled by HHWS. We apply spatially resolved climate projections, population estimates, and literature-derived exposure–response functions to quantify health outcomes across 1,447 urban areas in India. Sensitivity and envelope analyses assess the robustness of results to key assumptions.

We project 685,398 heat-related all-cause deaths and 353,014 heat-related preterm births between 2025 and 2035. Under enhanced intervention scenarios, HHWS could avert an additional 4,596 deaths and 6,354 preterm births compared to baseline interventions alone—representing reductions of 0.67% and 1.80%, respectively. While modest in scale, these findings demonstrate the potential for CSH to support anticipatory public health action and improve the timing, uptake, and coordination of existing interventions. However, results vary widely depending on implementation conditions, with envelope analyses indicating a potential range of 0 to 64,671 deaths and 0 to 42,890 preterm births averted.

Our findings highlight both the promise and the limitations of CSH. Realizing their full impact will require sustained investment in context-specific, user-informed climate services, and greater alignment between climate and health systems. More rigorous evaluation is also needed to strengthen the evidence base for CSH, and to identify the conditions under which they can most effectively reduce climate-sensitive health risks.

Keywords: Climate action, heat, temperatures, climate services, climate information, India, heat-related mortality, preterm births, heat action plans, heat health warning systems.

1. Introduction

Extreme heat, having increased in frequency, intensity, and duration due to climate change [1,2], poses significant health, social, and economic challenges. Each year, extreme heat causes 489,075 excess deaths globally [3–5], with disproportionate impacts on urban populations in low- and middle-income countries (LMICs), such as India [4,6–9]. Extreme heat also increases the risk of heat-related illnesses, exacerbates chronic health conditions, and has been associated with poor maternal and child health outcomes [10–14]. These changes strain health systems that are often ill-equipped to address the complex and dynamic effects of extreme heat due to a lack of robust and well-informed mechanisms to anticipate and act on its impacts [15–17]. This limitation hampers the ability of health systems to effectively plan, allocate resources, and deploy timely interventions, reducing their overall efficiency and effectiveness. Inadequate infrastructure limits the availability and quality of meteorological and health data, and the lack of integration between climate and health systems disrupts efforts to translate climate data into actionable health insights. As a result, public health responses remain reactive and fragmented, failing to mitigate the health consequences of extreme heat adequately. Addressing these challenges requires the integration of climate information into health systems, enabling evidence-based policymaking, proactive planning, and resource allocation to improve resilience and responsiveness against the rising threats of extreme heat.

Building climate-resilient and responsive health systems is a complex endeavor where several interrelated challenges persist. The availability and quality of meteorological and health information are often limited by inadequate infrastructure, hindering the ability to track and predict heat-sensitive health risks. Moreover, the lack of integration between heat and health systems disrupts efforts to translate climate data into actionable insights for health planning. Even when extreme heat predictions are available, weak early warning systems and barriers to information dissemination, such as limited access to digital technologies, prevent communities and health facilities from responding effectively.

These challenges are compounded by a shortage of trained personnel, poor coordination among health, meteorological, and urban planning sectors, and a lack of locally relevant, context-specific information. Together, these gaps create a fragmented system that struggles to anticipate and mitigate the health impacts of increasing extreme heat.

Addressing the fragmentation in climate and health systems requires innovative solutions that bridge the gap between information and action, and climate services for health (CSH) offer a compelling way forward. By integrating climate data into health decision-making, CSH enable governments and communities to better anticipate and respond to the health impacts of extreme heat, supporting adaptation and resilience-building efforts. These services rely on collaborative, multidisciplinary processes to co-develop solutions to guide preventative measures and strengthen health systems [16,18]. An example of CSH are heat-health warning systems (HHWS), which integrate meteorological information with heat-health risk assessments to provide timely warnings to emergency management and health and health-adjacent authorities before and during extreme heat, and cascading alerts allowing individuals or care givers to undertake preventive actions during extreme heat events. For HHWS to be effective, they must deliver scientifically credible, timely, and actionable information tailored to user needs, supported by strong partnerships and communication across sectors. However, fewer than one-quarter of Ministries of Health worldwide currently integrate climate information into their health surveillance systems and only half of all countries provide heat warnings [19]. The absence of widespread adoption highlights the untapped transformative potential of scaling-up initiatives like HHWS, which could save millions of lives in the coming decades [20].

There is a critical need for establishing smart HHWS [21] , globally, particularly in urban LMICs where extreme heat interacts with entrenched social, economic, and infrastructural vulnerabilities to exacerbate severe health risks. Urban heat is intensified by the urban heat island (UHI) effect, which raises local temperatures, especially in dense, unplanned settlements that often lack green spaces, reliable electricity, or cooling mechanisms such as air conditioning [22]. These conditions exacerbate heat-related illnesses like heatstroke and dehydration while worsening chronic health issues such as cardiovascular and respiratory diseases, alongside increasing risks of preterm births, maternal mortality, and neonatal complications [10–14]. Populations with pre-existing health vulnerabilities—such as the elderly, children, and outdoor workers—are disproportionately affected, especially in cities marked by pronounced income and socioeconomic inequities [23,24]. These challenges, commonly combined with overburdened health systems, leave cities ill-equipped to manage rising heat-related health threats. As extreme heat events grow more frequent and intense, the development and integration of HHWS offer a crucial opportunity to shift from reactive responses to proactive, evidence-based strategies. From predicting extreme heat episodes to guiding resource allocation and enhancing early response and risk communication, HHWS empower health systems to protect the most vulnerable and strengthen the capacity of health systems to withstand extreme heat.

Despite the growing recognition of their potential, HHWS remain significantly underutilized and understudied, particularly in the context of urban areas in LMICs [25]. While evidence from other sectors, such as agriculture, demonstrates the value of integrating climate information to reduce risks and increase intervention uptake [26–29], empirical research assessing the health impacts of such integration within health systems remains limited and, at best, inconclusive [30–32]. Systematic reviews have identified mixed results: some HHWS have been associated with reductions in heat-related mortality and increased public awareness, whereas others have shown minimal changes in health outcomes or behavior, particularly where barriers such as low risk perception, socioeconomic vulnerability, and inadequate communication persist [30,33]. This variability in evidence highlights the need for a deeper understanding of the potential of HHWS in protecting population health at risk from extreme heat. Expanding the evidence base is essential to inform policy, guide investment, and support the development of actionable frameworks that optimize the use of HHWS to protect vulnerable populations and strengthen health systems in the face of escalating heat risks.

This study seeks to address critical gaps in the literature by assessing the potential of HHWS to mitigate the adverse health impacts of extreme heat in urban settings. We draw on two case studies from urban India, each focused on a distinct health outcome—all-cause mortality and pre-term births—to address two primary objectives: first, to evaluate the adverse health impacts of extreme heat on urban populations; and second, to examine the potential contribution of HHWS in reducing these effects. To this end, we adapt the conceptual framework established by Mistry and Gasparrini [34], which predicts temperature-related excess mortality using publicly available data from the United Kingdom. We extend this methodology to the Indian context and expand it to quantify the potential role of HHWS in mitigating adverse heat-related health outcomes. Our analysis offers new insights to inform policy, investment, and practice in heat-vulnerable urban regions.

The remainder of our paper is organized as follows. Section 2 provides background information about our case studies. Section 3 reviews the framework and methods for our analysis. Section 4 presents the results. We discuss these findings and conclude in Section 5.

2. Background

To examine the potential of CSHs – specifically HHWS – to reduce the adverse health impacts of extreme heat, this study considers two theoretical case studies situated within a common geographic and temporal context: urban India from 2025 through 2035. Both case studies are set in the same national setting but explore distinct health outcomes—all-cause mortality and preterm births—chosen for their strong epidemiological associations with heat exposure and their significance as public health priorities in LMICs. This shared context enables a comparative lens on how improved climate-informed health services might influence diverse yet interrelated health outcomes in highly vulnerable populations.

The selected 11-year time horizon aligns with the next cycle of countries' Nationally Determined Contributions (NDCs), expected to be finalized in 2025 and targeting progress through 2035 [35]. This near-term window captures the urgent and intensifying impacts of extreme heat while reflecting the timeline over which HHWS could realistically be implemented, scaled, and evaluated for public health benefits.

Urban India offers a particularly compelling context in which to assess the potential of HHWS. The country experiences high levels of heat exposure, accounting for a substantial share of Asia's heat-related mortality, and faces significant structural vulnerabilities that heighten population-level risk. Nearly half of global heat-related deaths occur in Asia [3–5], with India bearing a disproportionate burden. Over 80% of the country is at risk of dangerous heat-related health effects (22), and mean annual temperatures are projected to increase by up to 3.5 degrees Celsius (°C) by mid-century (19–21). Projections also indicate that extreme heat events in India will not only intensify but also extend in duration, particularly during the monsoon months, when elevated humidity levels further amplify physiological heat stress and health risks [36–38]. In cities, the UHI effect can exacerbate exposure by raising temperatures as much as 10°C above surrounding rural areas [39], particularly in informal settlements that lack adequate housing, cooling infrastructure, green spaces, or reliable electricity [6,40]. With more than 520 million people living in urban areas [41]—nearly half of whom reside in informal or unplanned settlements [42] —India represents a strategic context for evaluating how climate-informed HHWS can improve adaptive capacity within health systems and reduce vulnerability among at-risk populations.

By integrating climate projections, health risk information, and health data, these case studies estimate the potential for improved HHWS to inform timely, targeted public health responses that reduce the burden of heat-related mortality and adverse birth outcomes. Together, they offer complementary insights into how climate services can be operationalized within health systems to protect population health amid escalating climate risks.

2.1 All-cause mortality and the role of HHWS in strengthening Heat Action Plans

All-cause mortality is a critical and widely used indicator for evaluating the health impacts of extreme heat, particularly in densely populated urban settings where risk factors often converge. It captures both the direct physiological effects of heat—such as heat exhaustion and heat stroke—and the indirect consequences, including the aggravation of chronic conditions like cardiovascular disease, respiratory disorders, and renal dysfunction [8,43,44]. These underlying conditions are especially prevalent among vulnerable populations, including older adults, outdoor workers, and those with limited access to cooling or health services [45]. The physiological stress induced by prolonged or extreme heat exposure can overwhelm the body's thermoregulatory mechanisms, leading to multisystem strain and elevated risk of death [46]. Empirical studies across Indian cities have consistently shown strong associations between rising temperatures and increased mortality risk, even at temperature thresholds lower than those observed in high-income countries [8,43]. In Ahmedabad, for example, a heatwave in 2010 was associated with a 43% rise in all-cause mortality, underscoring the serious public health implications of prolonged high temperatures in urban areas [47,48]. Even in the absence of officially declared heatwaves, cities such as Varanasi have reported a 5.6% increase in mortality associated with heat exposure, indicating that modest yet sustained temperature elevations can still lead to adverse health outcomes [48]. Given its epidemiological relevance and public health importance, all-cause mortality serves as a robust outcome for evaluating the potential of climate services for health to reduce heat-related health risks.

This case study examines the role of HHWS in enhancing the effectiveness of Heat Action Plans (HAPs)—India's principal public health strategy for managing extreme heat. HAPs are comprehensive, multisectoral frameworks designed to reduce heat-related morbidity and mortality through a combination of early warnings, public outreach, institutional coordination, and health system preparedness [47,49]. They aim to raise awareness among vulnerable populations, support anticipatory action by government agencies, and promote adaptive behaviors to reduce exposure [50]. As the institutional adoption of HAPs continues to expand across Indian cities [50], attention is increasingly turning to how climate-informed tools like HHWS can improve their operational impact. HHWS provide localized, lead-time-specific forecasts that can trigger tiered response actions across health and emergency systems. By improving the precision, timing, and targeting of HAP interventions, HHWS have the potential to significantly reduce excess mortality associated with extreme heat. This case study uses projected climate and health data to explore how integrating HHWS into HAP implementation could strengthen health system responses and reduce all-cause mortality in urban India.

2.2 Pre-term births and the role of HHWS in supporting maternal health interventions

Preterm birth—defined as delivery before 37 completed weeks of gestation—is a leading cause of neonatal mortality and long-term morbidity globally [51,52]. South Asia has the highest rate of preterm births globally, with 13.2% of live births affected, and India accounts for a significant portion of this burden. With a preterm birth rate of 13%, India ranks third globally [52], reflecting both the scale of the problem and the urgent need for targeted interventions. Emerging research has identified heat exposure as a significant and growing risk factor for preterm delivery. Studies indicate that each 1°C increase in temperature is associated with a 5% increase in the likelihood of preterm birth, while exposure to heatwave days raises the risk by as much as 16% [13]. Physiological mechanisms linking heat to preterm labor include dehydration, altered blood flow to the placenta, and elevated maternal stress responses [53,54]. Additionally, high temperatures may exacerbate underlying maternal health conditions, prompting medically indicated early deliveries [53]. Given both the high incidence of preterm births in India and the growing body of evidence connecting heat exposure to adverse pregnancy outcomes, preterm birth serves as a critical and underexplored health outcome for assessing how climate services for health can reduce risk.

This case study focuses on the potential role of HHWS in supporting targeted clinical interventions within maternal health systems, specifically the use of Atosiban, a tocolytic agent used to delay the onset of labor in cases of early contractions. Delaying labor, even briefly, can improve health outcomes by allowing time for antenatal corticosteroid administration, maternal stabilization, and transfer to a facility equipped for preterm care [55]. Atosiban is already approved for use in India [56], making it a feasible and contextually relevant intervention. Integrating HHWS into maternal care pathways—for instance, by ensuring that healthcare providers anticipate heat-related spikes in preterm labor risk—could strengthen the timeliness and targeting of such interventions. In this way, HHWS may serve not only as a tool for public health preparedness but also as a clinical decision-support mechanism within maternal health services. This case study explores the potential for pairing climate-informed early warnings with obstetric interventions to reduce the burden of heat-related preterm births and to improve outcomes for pregnant individuals and newborns in a warming climate. Integrating HHWS into maternal care pathways—for instance, by enabling healthcare providers to anticipate periods of elevated risk and prepare accordingly—could enhance the timeliness and effectiveness of these interventions. In this way, HHWS may serve not only as a tool for public health preparedness, but also as a foundation for anticipatory action within maternal health services, supporting proactive clinical decisions that reduce the burden of heat-related preterm births and improve outcomes for pregnant individuals and newborns in a warming climate.

Case study components are summarized in S1 Table.

3. Methods

We conduct a theoretical modelling exercise to estimate the potential reduction in heat-related adverse health outcomes resulting from the use of CSH, specifically HHWS. Our framework considers three distinct scenarios that build progressively on one another (Fig 1):

1. **No intervention scenario**: No public health intervention is implemented in response to heat exposure.
2. **Baseline intervention scenario**: A public health intervention is implemented with a standard level of effectiveness.
3. **Enhanced intervention scenario**: The same public health intervention is implemented with improved effectiveness due to the presence of a HHWS.

Fig 1. Logic models for the three scenarios of interest. In the no intervention scenario, no public health intervention is implemented in response to heat exposure and heat-related adverse health outcomes occur unchecked. In the baseline intervention scenario, a public health intervention is implemented with a standard level of effectiveness, thereby reducing the heat-related adverse health outcomes. In the enhanced intervention scenario, the same public health intervention is implemented with improved effectiveness due to the presence of a HHWS, thereby reducing the heat-related adverse health outcomes at an improved rate.

This framework is applied to the two illustrative case studies described above—all-cause mortality and preterm birth—each selected for their public health relevance, established association with heat exposure, and potential to benefit from timely interventions. The three-scenario structure allows us to simulate escalating levels of health system responsiveness and quantify the marginal impact of a HHWS.

We base our approach on the small-area forecasting framework developed by Mistry and Gasparrini (26), which estimates temperature-related excess health outcomes by coupling spatially resolved meteorological projections with exposure–response relationships derived from the epidemiological literature. This framework forms the foundation of Scenario 1, where no public health intervention is assumed. Scenario 2 builds directly on Scenario 1 by incorporating evidence on the effectiveness of public health interventions—such as Heat Action Plans or targeted clinical strategies—in mitigating heat-related adverse health outcomes. This allows us to estimate the reduction in adverse outcomes attributable to a standard, baseline intervention. Scenario 3 introduces the marginal benefit of a HHWS, operationalized as a scalar improvement in the effectiveness of the same public health intervention. This final layer captures the added value of integrating climate-informed early warnings into health system decision-making and action.

In the Section 3.1, we present the analytical equation used to quantify the effects described above and detail our data in Section 3.2. This approach specifically captures the difference in the expected reduction in heat-related adverse health outcomes between Scenario 2 and 3. It builds upon the results from Scenarios 1 and 2 to isolate the marginal contribution of a climate service for health, operationalized as the additional adverse health outcomes averted through climate-informed, anticipatory public health action.

3.1 Analytical approach

Our analytical approach quantifies the marginal contribution of a HHWS in reducing heat-related adverse health outcomes. Specifically, we estimate the additional number of outcomes averted due to the presence of a HHWS, assuming an underlying public health intervention is already in place. The number of heat-related adverse health outcomes averted associated with HHWS, i_{tu}, for each day, t, and urban area, u, is estimated as follows:

$$i_{tu} = \left(\frac{p_u \times a_u}{365.25}\right) \times (b_t - 1) \times c_t \times d.$$

where p_u denotes the total population of the urban area, while a_u reflects the baseline annual incidence of the selected health outcome. Together, these yield the estimated baseline daily incidence of the health outcome when divided by 365.25. The term b_t corresponds to the relative risk of the health outcome associated with heat exposure on day t. The term c_t captures the relative risk reduction due to an existing public health intervention on day t. Finally, d represents the percentage point change in the intervention's effectiveness attributable to the HHWS.

By summing i_{tu} across all urban areas and across the full modelling period, we estimate the total marginal impact of a HHWS.

To assess robustness, we conduct a sensitivity analysis, in which each parameter is varied independently while holding others constant. We also perform an envelope analysis, adjusting multiple parameters simultaneously to their respective upper and lower bounds, to generate a range of plausible estimates. Full details on assumptions, parameter values, and analytical code are provided in the supporting information.

3.2 Data

In this section, we describe the key data inputs used in our modelling exercise, including demographic, climatic, and epidemiological data, as well as the core assumptions underpinning our estimates of exposure–response relationships and intervention effectiveness. All data sources are publicly available. A summary of the main data sources is provided below, with further details—including data ranges, citations, and parameter values—presented in the supporting information. Data processing and analysis code are available on Zenodo [57].

Urban areas and population. To estimate historical population for each urban area, we use the WorldPop Global Project's Estimated Residential Population dataset [58], which provides gridded population data at 100-meter resolution. We calculate total population by summing gridded population estimates across each urban shapefile using Google Earth Engine. For forward-looking population estimates, we project urban-level population by coupling these historical estimates with the annual urban population growth rate of the nearest urban agglomeration, as reported in the United Nations Population Division's World Urbanization Prospects [59]. We identify the nearest urban agglomeration for each urban area spatially within Google Earth Engine. These data are aggregated to urban boundaries and used to estimate both baseline annual incidence and per capita impact of heat-related adverse health outcomes. We conduct all geospatial and population calculations in Google Earth Engine and extract data using the R package "rgee".

For the all-cause mortality case study, we use crude mortality rates as a proxy for baseline all-cause mortality. We collect state-level projected crude mortality rates from India's 2011 census [60] and apply these rates to each urban area based on its geographic location.

For the preterm birth case study, we estimate projected preterm birth rates at the state level by combining multiple publicly available data sources. We use the population projections described above, state-level urban birth rates from 2016 [61], national birth rate projections [59], and national estimates of the proportion of births that are preterm [52]. This approach allows us to generate baseline estimates of preterm birth rates consistent with spatial population projections and epidemiological risk.

Temperature. We extract daily mean and maximum near-surface air temperature projections under the SSP245 climate change scenario from NEX-GDDP-CMIP6 [62] using Google Earth Engine. This dataset provides statistically downscaled climate projections from multiple general circulation models (GCMs) at approximately 25 km spatial resolution, enabling consistent spatial coverage across India's urban areas.

To ensure alignment with the spatial scale of urban environments, we resolve temperature data to a 30-kilometer diameter buffer centered on the centroid of each urban area.

We define *extreme heat* as any day on which the mean daily temperature is equal to or exceeds 31°C. This threshold is informed by recent research by Vanos et al., 2023 [63], which demonstrates that traditional upper limits of human thermal survivability—particularly wet-bulb temperatures of 35°C—are likely overestimated. The study highlights that in hot-dry conditions, survivability thresholds for extreme heat can be substantially lower, suggesting the need for a more conservative approach. By adopting a 31°C threshold, we align with updated understanding of human thermal tolerance that accounts for physiological variation, regional environmental conditions, and real-world vulnerability. We consider temperature increases in 0.5°C and 1.0°C increments, consistent with the resolution of available exposure–response relationships and to facilitate sensitivity analysis around heat-health thresholds.

Exposure-response relationships. We identify temperature dose–response relationships for both case studies—all-cause mortality and preterm birth—through a rapid scan of the peer-reviewed literature. These relationships estimate the change in health risk associated with extreme heat and serve as a core input to our modelling framework.

For the all-cause mortality case study, we extract temperature-dependent relative risk estimates from Dimitrova et al. [43], who report exposure–response ratios based on daily mean temperature. Consistent with this study, we consider the daily mean near-surface air temperatures as our exposure temperature.

For the preterm birth case study, we construct exposure–response ratios by coupling historical temperature data with odds ratios reported in Lakhoo et al. [64], who estimate the increase in risk of preterm birth associated with each 1°C rise in temperature. We calculate the historical mean temperature as the average daily temperature from 2015 through 2024, and use deviations from this baseline to apply the estimated temperature-related risk increases.

We include the full range of risk estimates, confidence intervals, and sources used for each health outcome in S2 and S3 Tables.

Public health intervention effectiveness. We incorporate estimates of public health intervention effectiveness for each case study based on peer-reviewed literature and expert-informed assumptions. These interventions represent the baseline level of health system response assumed to be in place in the absence of a HHWS. We include the full range of risk estimates, confidence intervals, and sources used for each public health intervention in S4 and S5 Tables.

For the all-cause mortality case study, we use effect estimates from Hess et al. [49], who evaluate the impact of HAPs in Ahmedabad, India. Their findings suggest that HAPs can reduce heat-related mortality through proactive communication, public awareness campaigns, and enhanced health system preparedness. We apply the relative risk reductions reported in this study to estimate the effect of a baseline intervention scenario.

For the preterm birth case study, we incorporate findings from Wilson et al. [55], who evaluate the effectiveness of Atosiban, a tocolytic agent used to delay the onset of labor. While the study is not heat-specific, we use its findings to estimate the benefit of clinical intervention in reducing preterm births among individuals experiencing early labor triggered by heat stress. We assume that this intervention is traditionally implemented reactively under standard care conditions and apply the relative risk reductions reported in this study to estimate the effect of a baseline intervention scenario.

We assume that the presence of a HHWS enhances the effectiveness of these public health interventions by improving when, where, and how they are implemented. In practice, a HHWS could improve effectiveness by increasing the frequency with which an intervention is activated (for example, by enabling more accurate identification of extreme heat days that trigger HAPs), increasing the uptake of the intervention (such as improving clinical awareness and readiness to administer Atosiban during anticipated high-risk periods), or enhancing the overall quality and coordination of implementation (by enabling better targeting, communication, and preparedness even when the intervention is deployed the same number of times). These mechanisms reflect practices aligned with the spirit of anticipatory action and are supported by evidence from other sectors, including agriculture, disaster risk reduction, and humanitarian response, which consistently demonstrate that early warning systems improve outcomes when they enable earlier and better-informed decisions [26–29,65,66].

For simplicity, our model assumes that HHWS increases effectiveness through either more frequent implementation of the intervention or improved uptake among the target population. This abstraction allows us to quantify one plausible mechanism of impact while acknowledging the broader, more complex ways HHWS may support system-wide responsiveness. We assume that HHWS improves intervention effectiveness by 10% in our primary analysis. This estimate is informed by both the cross-sectoral literature and informal conversations with relevant public health and climate services stakeholders, who expressed consensus that such a magnitude of benefit is both reasonable and conservative. We test a wider range of 5% to 20% improvements in sensitivity analyses to account for uncertainty and contextual variation.

4. Results

Our analysis includes 1,447 urban areas across India, collectively covering approximately 31,000 km^2, or about 1% of the country's total land area. These areas represent an estimated 239 million urban residents in 2025, with the population projected to grow to 297 million by 2035, based on demographic and urban growth projections.

Across the 11-year modelling period (2025–2035), the average projected daily mean temperature across all urban areas is 26.98°C (SD = 4.71), with temperatures ranging from –20.49°C to 45.98°C. The highest daily mean temperatures are expected across urban areas in southern India, particularly in Andhra Pradesh, Goa, and Telangana. In contrast, northern regions—including Ladakh, Sikkim, and Jammu and Kashmir—are projected to experience the lowest daily mean temperatures during the analysis period (Fig 2, Panel A).

Fig 2. Mean daily temperature and number of annual extreme heat days by urban area (2025-2035). (A) Mean daily temperature in Celsius across 2025-2035. (B) Average number of days above 31°C (i.e. an extreme heat day) per year across 2025-2035.

Over the modelling period, urban areas experience considerable variation in the number of days exceeding the 31°C extreme heat threshold, with an increasing trend in heat exposure over time. Urban areas in Rajasthan (1,295 days) and Punjab (1,196 days) are projected to experience the highest cumulative number of extreme heat days, while several northeastern and high-altitude states—such as Ladakh, Sikkim, Manipur, Meghalaya, and the Andaman and Nicobar Islands—are expected to experience no days above this threshold (Fig 2, Panel B). Over 600 urban areas are projected to spend at least 25% of each year under conditions of extreme heat (S6 Fig), underscoring the widespread and recurrent nature of the exposure across the urban landscape.

4.1 All-cause mortality

While we define extreme heat as any day on which the mean daily temperature is equal to or exceeds 31°C, our theoretical HAP is only triggered when the maximum daily temperature exceeds 40°C, with low, moderate, and high alert levels based on how far the maximum temperatures exceeds this threshold (S3 Table). Our analysis considers 1,447 urban areas across 11 years for a total of 5,812,599 urban area-days. Of those urban area-days, 21% are extreme heat days (mean daily temperature exceeds 31°C) but only 9% are extreme heat days and trigger a HAP (mean daily temperature exceeds 31°C and maximum daily temperature exceeds 40°C). The majority of extreme heat days fall within the lower-threat, yellow alert band (43%), while higher-threat, red alert conditions—triggering the strongest intervention protocols—comprise 8% of all extreme heat days that trigger a HAP. These red-alert urban-area days are concentrated in states such as Maharashtra, Uttar Pradesh, and Rajasthan. These classifications inform the frequency with which interventions are modelled as deployed under both baseline and enhanced scenarios.

Heat-related mortality varies substantially across the country. Fig 3 visualizes population-adjusted mortality across urban areas, revealing high concentrations of risk in northern and central India, with the highest rates observed in Rajasthan and Chhattisgarh (Fig 3, Panel A). When a HHWS is introduced (Fig 3, Panel B), the additional lives saved are most concentrated in these same regions, particularly in Chhattisgarh and Madhya Pradesh, where both exposure and underlying vulnerabilities intersect.

Fig 3. Heat-related all-cause mortality expected and averted by urban area per 1,000 people (2025-2035). (A) Heat-related all-cause mortality expected if no HAP is implemented. (B) Heat-related all-cause mortality averted due to a CSH. Results are normalized by the urban area's population for each year individually and then aggregated across all years.

Between 2025 and 2035, under the no-intervention scenario, we project a total of 685,398 all-cause deaths associated with heat. Under the baseline intervention scenario, implementation of HAP alone is projected to avert 45,957 deaths, while the enhanced intervention scenario, which incorporates a HHWS, is projected to avert 50,553 deaths. The marginal contribution of the HHWS is therefore 4,596 additional deaths averted over the 11-year period.

Fig 4 presents all-cause mortality averted due to a CSH by year. Variation between years is a result of annual temperature variance, growing populations, and changing mortality rates. The expected and averted heat-related all-cause mortality by state and by year are presented in S7 and S8 Tables, respectively.

Fig 4. Heat-related all-cause mortality averted due to a CSH by year (2025-2035). The spikes in heat-related all-cause mortality averted in 2029, 2033 and 2035 are a result of hotter temperature projections for those years in combination with a growing population over time.

4.2 Preterm births

Between 2025 and 2035, we project a total of 353,014 preterm births associated with heat exposure across the 1,447 urban areas included in our analysis. Under the baseline intervention scenario, the administration of Atosiban, a tocolytic agent used to delay early labor, is estimated to avert 63,543 of these preterm births. In the enhanced intervention scenario, in which the administration of Atosiban is coordinated through a HHWS, a total of 69,897 preterm births are averted. This represents a marginal contribution of 6,354 preterm births averted due to the improved targeting and timeliness of intervention made possible by the HHWS.

Geographic variation in heat-related preterm births is notable. Fig 5 presents spatial variation in the burden of preterm births. As with all-cause mortality, the population-adjusted burden of heat-related preterm births is distributed across India but is particularly concentrated in northern states, with the highest rates observed in Uttar Pradesh and Rajasthan (Fig 5, Panel A). When the HHWS is introduced (Fig 5, Panel B), the marginal benefits—i.e., the additional preterm births averted—are also greatest in these regions, reflecting similar patterns of exposure and vulnerability seen in the mortality case study.

Fig 5. Total preterm births expected and averted by urban area per 1,000 people (2025-2035). (A) Heat-related preterm births expected if Atosiban is not administered. (B) Heat-related preterm births averted due to a CSH.

Fig 6 presents all-preterm births averted due to a CSH by year. Variation between years is a result of annual temperature variance, growing populations, and changing preterm birth rates. The expected and averted heat-related preterm births by state and by year are presented in S9 and S10 Tables, respectively.

Fig 6. Heat-related preterm births averted due to a CSH by year (2025-2035). The consistent increase in heat-related preterm births averted starting in 2032 is a result of increasingly hotter temperature projections for those years in combination with a growing population over time.

4.3 Sensitivity and envelope analyses

We conduct both sensitivity analyses and envelope analyses to assess the robustness of our results to changes in key parameters and assumptions. Detailed parameter ranges and methods are provided in S11 and S12 Tables.

All-cause mortality. Our sensitivity analysis suggests that projected impacts on heat-related all-cause mortality are sensitive to parameter variation. We find that the model is most sensitive to the effectiveness of the HAP—that is, the exposure–response relationship between HAP implementation and mortality reduction. Conversely, our results are least sensitive to changes in the exposure–response relationship between heat and all-cause mortality, suggesting relative stability in estimating the baseline health burden of heat. This suggests that the demonstrated marginal value of a HHWS in this case study is driven by how it improves the HAP reduces mortality.

The envelope analysis further illustrates the range of potential outcomes under lower- and upper-bound parameter assumptions. In this analysis, the estimated impact of the HHWS ranges from 0 to 64,671 deaths averted, reflecting the extent to which the modelled effectiveness of public health interventions and the assumed added value of a HHWS influence overall outcomes. The lower bound indicates that under certain combinations of conservative assumptions, the HHWS may produce no additional mortality benefit, while the upper bound suggests that it could significantly reduce the burden of heat-related mortality. Together, these findings highlight both the uncertainty and the potential of HHWS to strengthen responsiveness to heat-related risks.

The results of the sensitivity and envelope analyses for all-cause mortality are presented in S13 and S14 Tables, respectively.

Preterm births. In contrast, results for the preterm birth case study are generally more robust to parameter variation. Sensitivity analysis indicates that the results are most sensitive to changes in the assumed improvement in intervention effectiveness due to the HHWS, and least sensitive to changes in the exposure–response relationship between heat and preterm birth. This suggests that the demonstrated marginal value of a HHWS in this case study is also driven more by the clinical intervention than by uncertainty in the underlying heat-risk function.

Envelope analysis confirms this robustness, showing a range of 0 to 42,890 preterm births averted across the lower- and upper-bound parameter combinations. While the lower bound reflects the possibility of no marginal benefit from the HHWS under conservative assumptions, the upper bound suggests that HHWS could substantially enhance the effectiveness of maternal health interventions. These findings underscore the uncertainty in estimating the marginal impact of HHWS, but also highlight its potential value in strengthening maternal health preparedness to rising heat exposure, particularly when implementation conditions are favorable.

The results of the sensitivity and envelope analyses for preterm births are presented in S15 and S16 Tables, respectively.

5. Discussion

Our study predicts the adverse health impacts of heat on urban populations in India, focusing on all-cause mortality and pre-term births, and explores the potential role of a CSH in mitigating these risks. By applying and extending the operational framework established by Mistry et al. (2024) to a South Asian context, we illustrate how a CSH, specifically a HHWS, can enhance existing public health interventions by predicting heat-related health risks, identifying vulnerable populations, and improving the design and targeting of interventions. From 2025 through 2035, we project over 685,400 cases of heat-related all-cause mortality and 353,000 heat-related preterm births across urban India. Under baseline assumptions, a HHWS has the potential to avert approximately 4,600 all-cause deaths and 6,350 preterm births, representing a reduction of 0.67% and 1.80%, respectively. While modest, these findings suggest that HHWS can serve as a foundation for introducing a broader framework of anticipatory action and proactive public health planning in this setting. Rather than reacting to health emergencies after they occur, HHWS enable earlier identification of risk and the activation of responses that can prevent harm—such as scaling up municipal heat preparedness or initiating timely clinical interventions. In this way, HHWS represent a shift from crisis management to preventive action, offering a strategic tool for health systems to reduce vulnerability and protect population health in India's rapidly urbanizing environments.

While the overall health impact of a HHWS appears modest in magnitude, it signals meaningful progress toward climate-resilient public health systems. Our main analysis suggests that HHWS can avert an average of 418 heat-related deaths and 578 preterm births each year across urban India. Although these figures are small relative to the country's large urban population, they underscore the untapped potential of climate services to protect health. Importantly, these outcomes reflect only two health endpoints, and likely represent a conservative estimate of the broader protective benefits of CSH. Results from our robustness analyses further reveal that the impact of HHWS is likely to be highly sensitive to the enabling environment in which it is introduced. Specifically, the wide variation in impact across sensitivity and envelope analyses stems from changes in parameters related to how the intervention is implemented, rather than the underlying epidemiological risk. This suggests that the effectiveness of HHWS depends not only on the accuracy of heat forecasts, but also on how well early warnings are integrated into public health protocols, how prepared frontline systems are to respond, and whether target populations are equipped and willing to act. Thus, poor implementation of CSH—characterized by weak institutional coordination, inadequate public communication, or limited response capacity—can dilute the intended effect [67], leading to null outcomes, as reflected in the zero-effect lower bound observed in our envelope analysis for all-cause mortality.

Conversely, the upper-bound scenario in our analysis—where the HHWS is assumed to trigger timely, targeted, and well-coordinated interventions—demonstrates the substantial potential of these systems under optimal conditions. In this scenario, the HHWS is fully embedded within a well-functioning public health infrastructure: alerts are issued early and accurately, health systems have pre-positioned resources and clear protocols, and local actors (including health workers, municipal agencies, and communities) are aware of and responsive to warnings. This combination of high forecast reliability, institutional readiness, inter-agency coordination, and public engagement defines a best-case scenario that can maximize the health-protective value of HHWS. As such, our findings highlight the need not only to invest in the development of CSH, but also to strengthen the systems that surround and sustain them—including governance mechanisms, implementation capacity, and the social infrastructure needed for effective risk communication and uptake.

This study has three main limitations. First, we assume an urban population that is half of the urban population estimated by the World Bank, which reported nearly 523 million people in 2023 (46). This discrepancy likely arises from Data for Good's more restrictive definition of urbanicity and exclusion of fringe or peri-urban areas, thus resulting in a lower urban population count. Therefore, our estimates represent a conservative assessment of the total potential impact of a HHWS. Second, our findings rely on the assumption that a CSH, like a HHWS, improves the delivery of public health interventions. However, there is limited understanding of how a CSH can enhance the effectiveness of existing public health measures. Our assumption was informed by studies from sectors that utilize climate information [26–29] and consultations with experts in the field. As evidenced by our robustness analyses, the success of integrating a CSH into public health intervention delivery is highly dependent on this assumption, underscoring the need to strengthen the enabling environment to fully realize the benefits of CSH. Third, although our current model does not explicitly incorporate seasonal humidity or wet-bulb temperature, we acknowledge the growing evidence that humid heat extremes during the monsoon season pose substantial risks to health [68]. These conditions can reduce the body's ability to thermoregulate and may lead to elevated risks even when dry-bulb temperatures remain moderate [69]. Future work could integrate humidity-sensitive metrics to better capture these compounding risks.

The growing global momentum for expanding CSH —as reflected in initiatives such as the WMO–WHO Joint Climate and Health Programme [19]—underscores the importance of embedding climate-informed tools like HHWS into public health programming. However, evidence to date suggests that simply introducing these systems is not sufficient. A systematic review by Toloo et al. [30] identified fifteen studies examining the effectiveness of HHWS. While several studies reported modest improvements in public awareness and reductions in mortality—particularly among older populations—most showed little to no measurable change in health outcomes or behavior, pointing to persistent barriers in system design and implementation. These include low public risk perception, economic constraints, and limited reach among the most vulnerable groups [32]. When viewed alongside our findings, which highlight significant variability in HHWS effectiveness depending on the implementation context, this body of evidence makes clear that creating an enabling environment is essential for realizing the full potential of CSH.

Building such an environment requires coordinated efforts across multiple domains and stakeholders. Jones et al. [70] identify five categories of constraints that often impede the effective uptake and use of climate services: (1) disconnections between the users and producers of climate information, (2) limitations in the quality and usability of climate information, (3) financial and technical resource constraints, (4) political economy and institutional barriers, and (5) psycho-social dynamics, including trust and perceived relevance. Overcoming these constraints demands investment in both the supply and demand sides of the climate–health interface. This includes fostering collaboration and "bridging work" between sectors, improving the accessibility and granularity of climate information, enhancing the underlying scientific and modelling infrastructure, and seizing political windows of opportunity for reform and trust-building [70].

This emphasis on collaboration is echoed by Goddard et al. [71] who argue that cross-sectoral partnerships—particularly those that bring together scientists, municipal authorities, and public health policymakers—can strengthen institutional capacity, increase legitimacy, and improve the long-term sustainability of climate response strategies. Central to this approach is the development of two-way communication channels and ongoing relationships between stakeholders, which enable tailored climate information, better alignment with user needs, and iterative refinement of interventions. These relational and institutional elements are not peripheral to the success of CSH—they are core to their legitimacy, usability, and effectiveness.

Advancing the field of CSH requires urgent attention to two critical and interdependent priorities. First, there is a clear and pressing evidence gap: we still do not fully understand whether, how, and under what conditions CSH are effective at delivering health benefits. Empirical evaluations of CSH remain limited in both number and scope, with little consensus on which configurations lead to improved outcomes or how these benefits may vary across settings. More rigorous and contextually grounded research is needed to assess not only the direct health impacts of CSH but also their co-benefits, such as improved planning, reduced response time, and strengthened institutional relationships. Without such evidence, efforts to expand CSH risk being driven more by aspiration than demonstrated impact.

Second, there is a need for sustained and strategic investment—not just in enhancing the effectiveness of joint CSH and public health interventions, but in developing CSH themselves. These services must be designed explicitly to inform public health action, grounded in local needs, and developed in collaboration with the users they are intended to serve. Building responsive and effective CSH requires more than integrating existing data streams—it involves designing climate information services that are timely, usable, and actionable within the specific constraints and capacities of public health institutions.

Successful integration depends on strengthening key processes and enabling factors, which vary across contexts. Many countries face systemic barriers to integration, including underdeveloped early warning infrastructure, poor connectivity between climate and health sectors, and challenges in disseminating timely and relevant information. Addressing these barriers requires investment in locally tailored approaches that align with the realities of diverse institutional, socio-political, and environmental settings. In some contexts, priority actions may include improving the availability, granularity, and usability of climate and health data to support more precise risk assessments and localized interventions. In others, the focus may need to be on fostering intersectoral coordination, strengthening governance and institutional frameworks, and building long-term capacity across climate and health systems. Without such targeted and coordinated action, the health impacts of climate change—particularly those associated with extreme heat—will continue to escalate, placing increasing strain on public health systems and deepening inequalities among vulnerable populations.

6. Conclusions

As climate change accelerates, the need for timely, actionable, and health-protective responses becomes increasingly urgent. Our study contributes to a growing body of evidence on the health risks of extreme heat in urban India and the potential for health interventions enhanced by CSH to reduce those risks. While the estimated reductions in heat-related mortality and preterm births may appear modest in scale, they highlight a meaningful opportunity for health systems to act earlier, more effectively, and with greater precision in the face of rising climate threats. Importantly, our findings illustrate that the impact of CSH is not uniform—it is shaped by the context in which it is implemented and by the strength of the systems surrounding it. To realize the full potential of CSH, greater investment is needed not only in scaling up these tools but in designing them for relevance, equity, and usability within the public health systems they aim to support. The path forward will require deeper evidence, sustained collaboration, and a clear commitment to strengthening the enabling conditions that allow CSH to inform and improve public health action in a changing climate.

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Supporting information

S1 Table. Case study components

S2 Table. Exposure-response ratios for heat on all-cause mortality

S3 Table. Exposure-response ratios for heat on pre-term births

S4 Table. Effect of a Heat Action Plan on all-cause mortality

S5 Table. Effect of Atosiban administration on the delay of pre-term births by seven days

S6 Fig. Number of urban areas by average number of extreme heat days per year

S7 Table. Heat-related all-cause mortality by state (2025-2035)

S8 Table. Heat-related all-cause mortality by year (2025-2035)

S9 Table. Heat-related preterm births by state (2025-2035)

S10 Table. Heat-related preterm births by year (2025-2035)

S11 Table. Sensitivity analyses parameters

S12 Table. Envelope analyses parameters

S13 Table. Sensitivity analysis results for all-cause mortality

S14 Table. Envelope analysis results for all-cause mortality

S15 Table. Sensitivity analysis results for preterm births

S16 Table. Envelope analysis results for preterm births

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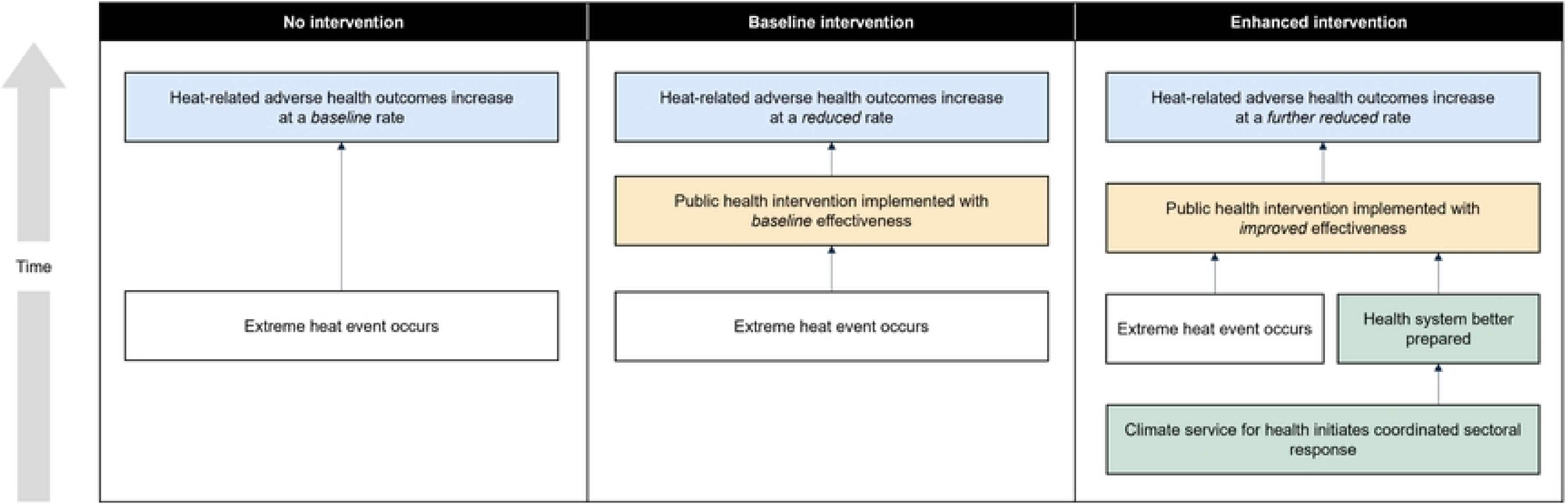

No intervention
Baseline intervention
Enhanced intervention
Time
Heat-related adverse health outcomes increase at a *baseline* rate
Extreme heat event occurs
Heat-related adverse health outcomes increase at a *reduced* rate
Public health intervention implemented with *baseline* effectiveness
Extreme heat event occurs
Heat-related adverse health outcomes increase at a *further reduced* rate
Public health intervention implemented with *improved* effectiveness
Extreme heat event occurs
Health system better prepared
Climate service for health initiates coordinated sectoral response

Figure1

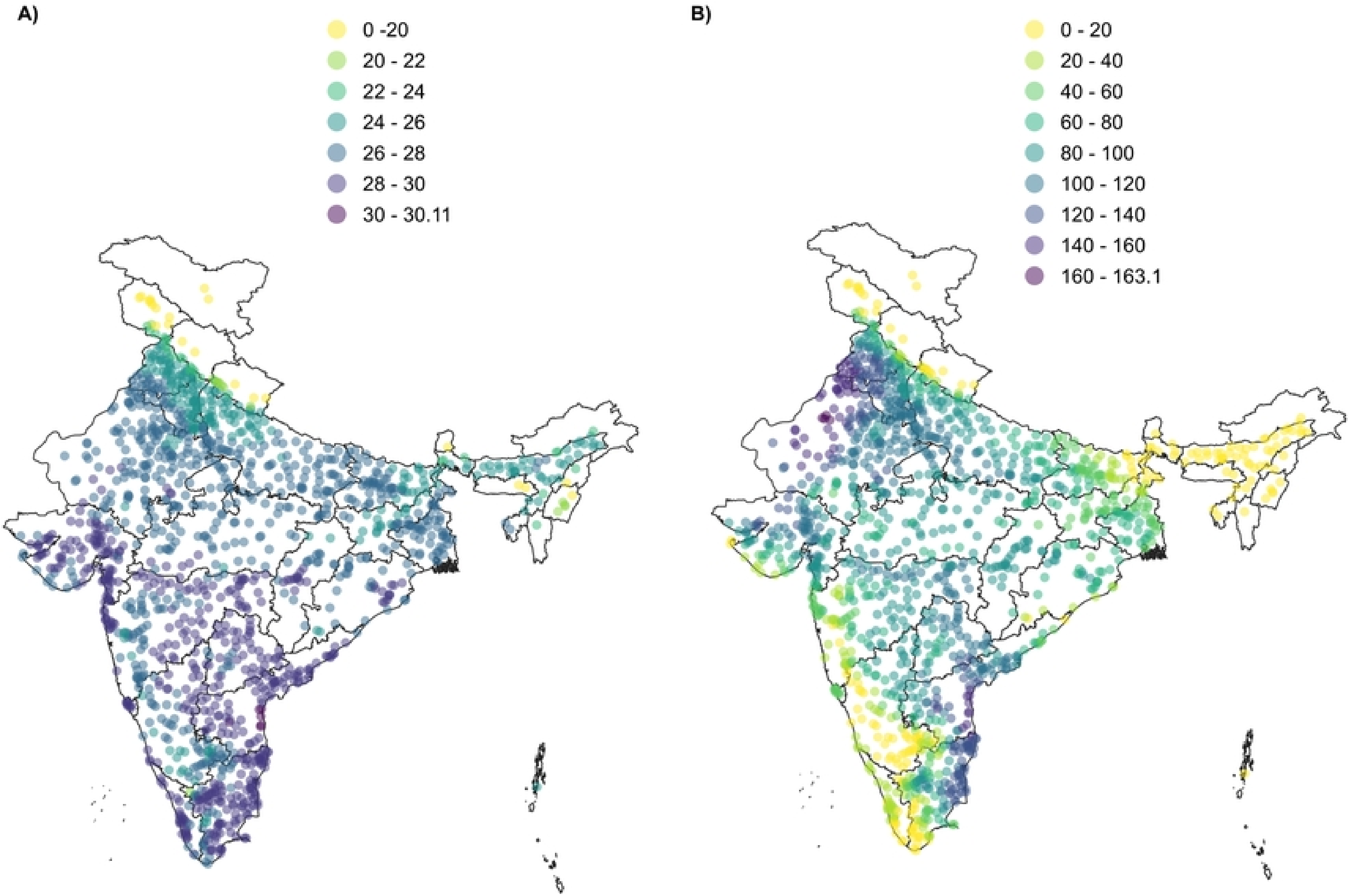
A)
0 -20
20 - 22
22 - 24
24 - 26
26 - 28
28 - 30
30 - 30.11
B)
0 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 120
120 - 140
140 - 160
160 - 163.1

Figure2

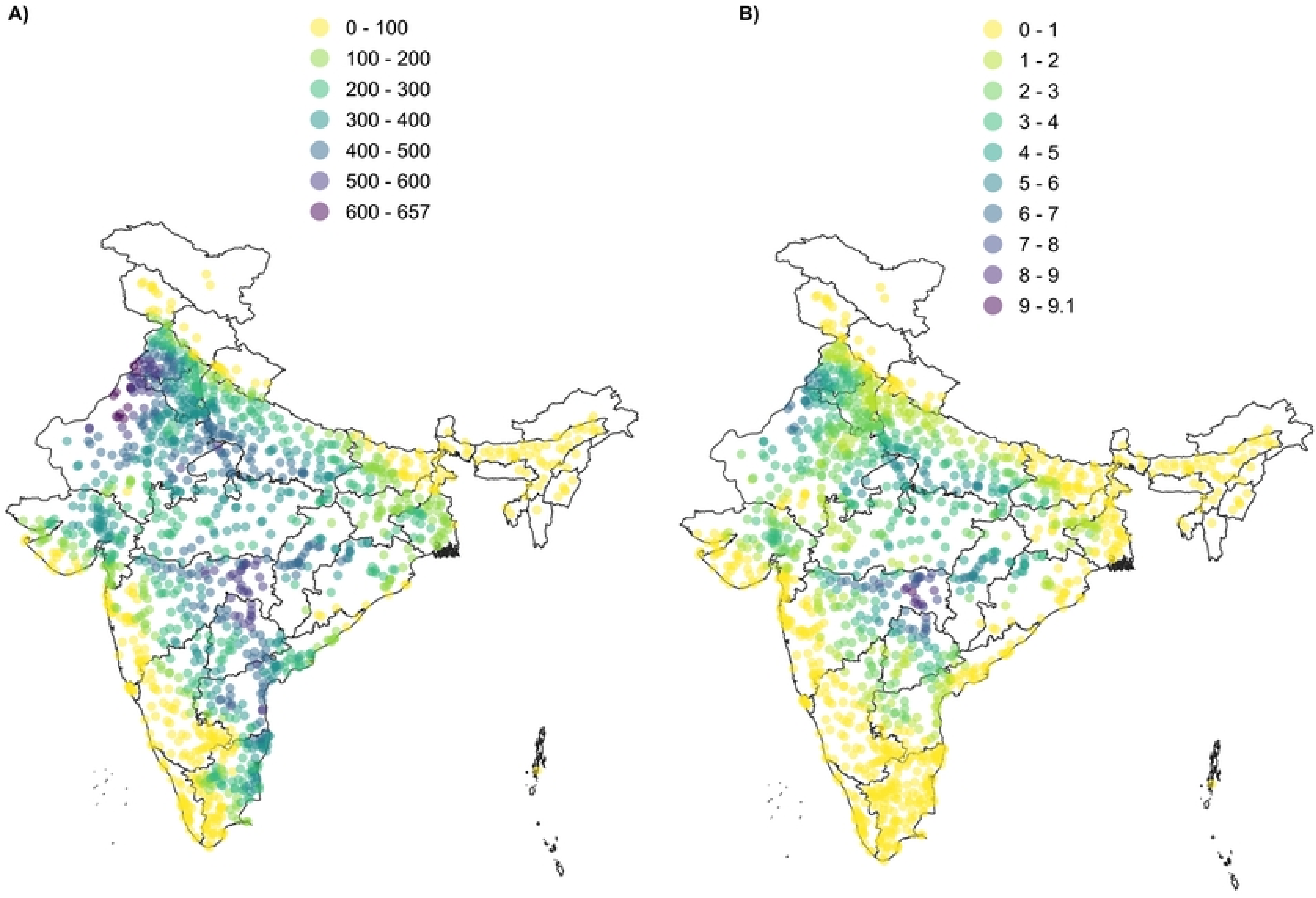
A)
0 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 657
B)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
9 - 9.1

Figure3

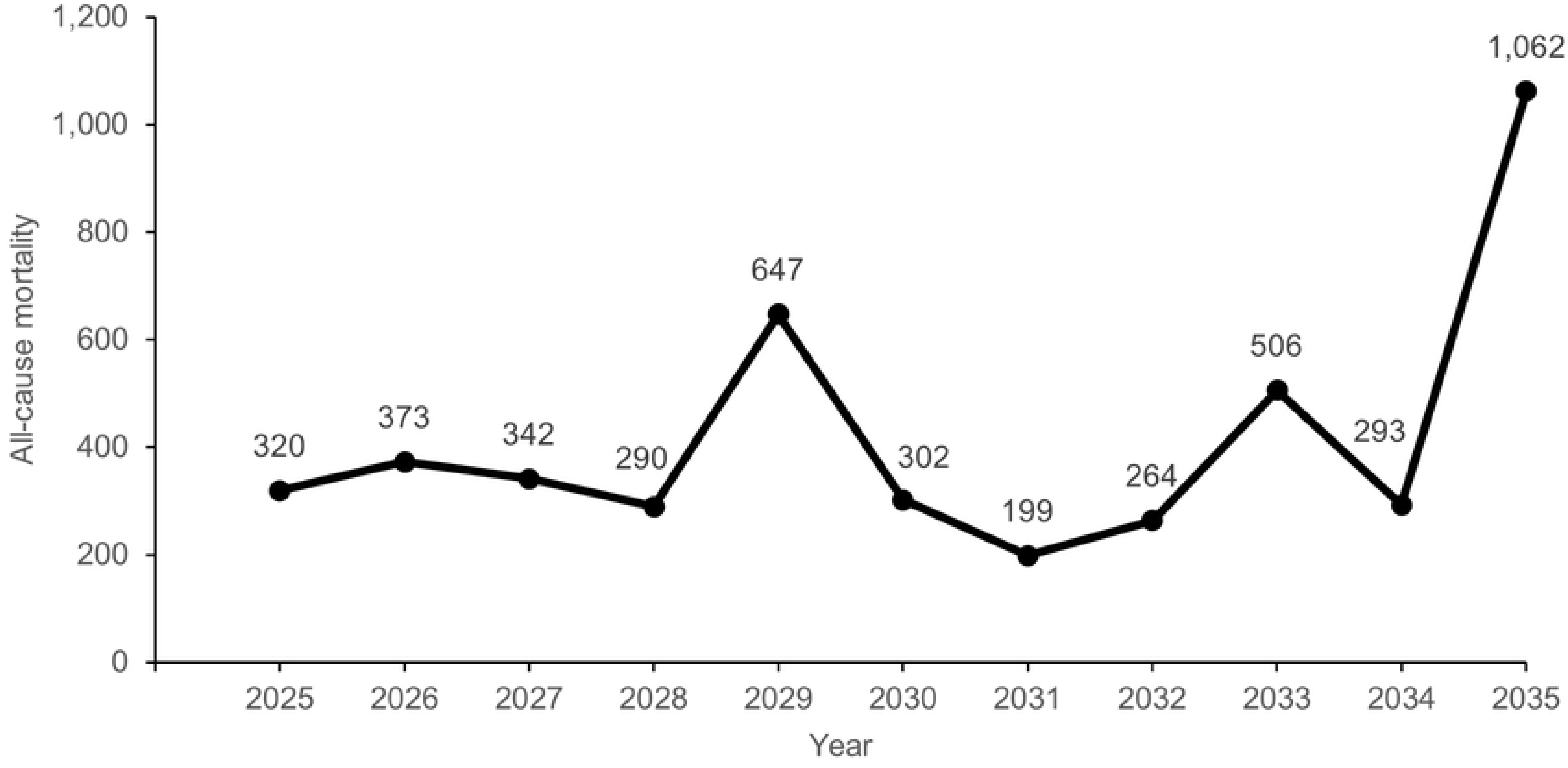
1,200
1,000
800
600
400
200
0
All-cause mortality
320
373
342
290
647
302
199
264
506
293
1,062
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
Year

Figure4

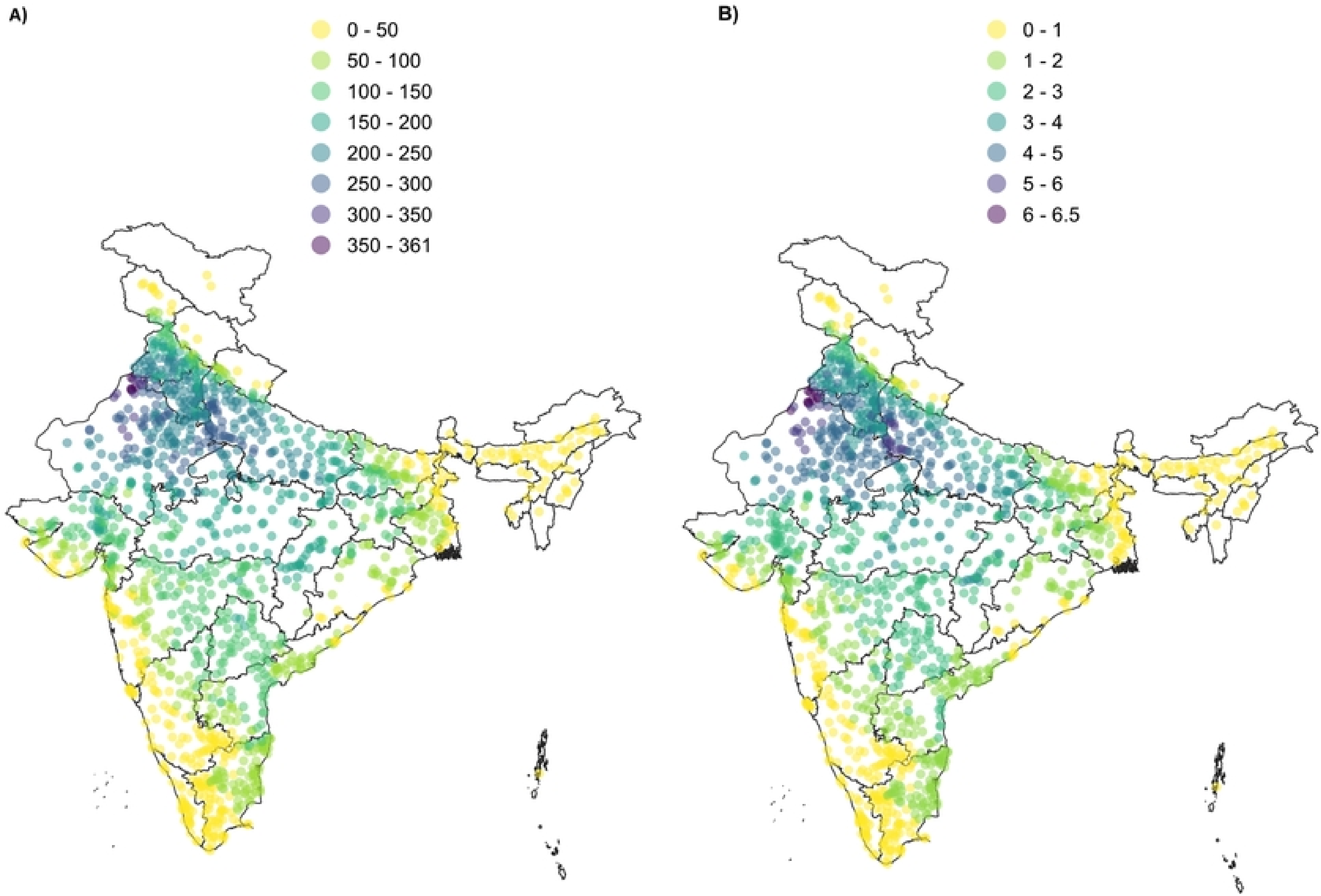
A)
0 - 50
50 - 100
100 - 150
150 - 200
200 - 250
250 - 300
300 - 350
350 - 361
B)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 6.5

Figure5

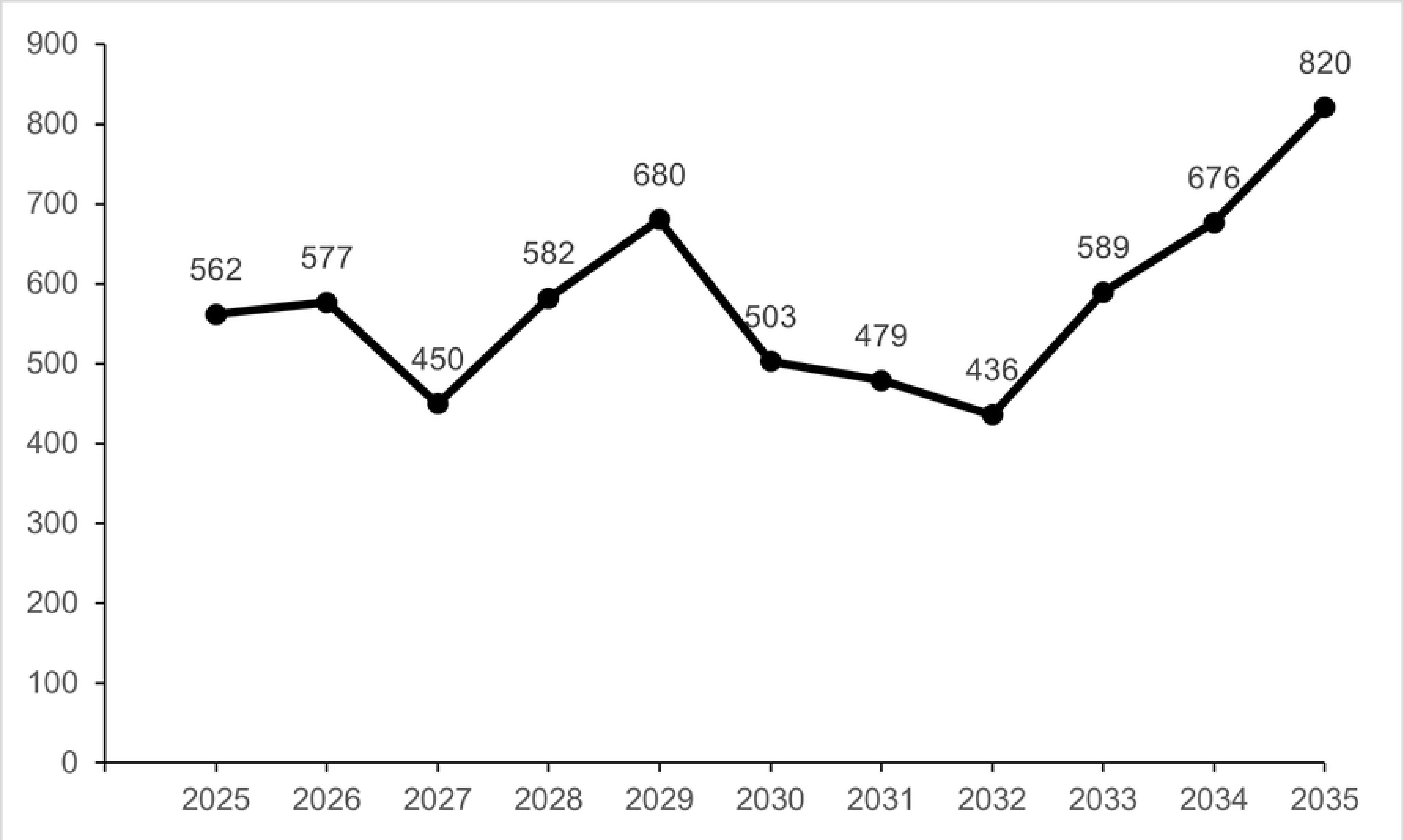
900
800
700
600
500
400
300
200
100
0
562
577
450
582
680
503
479
436
589
676
820
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035

Figure6