Effects of climate change on physical inactivity: a panel data study across 156 countries from 2000 to 2022

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Summary

Background Climate change is amplifying heat exposure worldwide; however, its consequences for global physical inactivity, and the resulting effects on mortality and economic burden, remain unquantified.

Methods We analysed a longitudinal dataset spanning 156 countries from 2000 to 2022 using a binned fixed-effects panel regression model. The model examined the relationship between the primary outcome—the age-standardised prevalence of physical inactivity in adults (aged ≥18 years)—and annual exposure to different temperature ranges. Estimated exposure coefficients and climate projections under different shared socioeconomic pathways (SSPs) were used to forecast future physical inactivity. Using relative-risk estimates for all-cause mortality, we converted projected physical inactivity into excess deaths and valued lost productivity using a friction-cost approach calibrated to each country's gross domestic product and labour participation rates.

Findings Each additional month with a mean temperature >27·8°C increased physical inactivity by 1·44 (95% CI 0·49–2·39) percentage points globally and 1·85 (0·62–3·08) percentage points in low-income and middle-income countries. By 2050, the prevalence of physical inactivity is projected to rise by 0·98 (0·47–1·49) percentage points under SSP1–2.6, 1·22 (0·58–1·85) percentage points under SSP2–4.5, and 1·75 (0·84–2·66) percentage points under SSP5–8.5, with hotspots exceeding 4 percentage points in Central America, the Caribbean, eastern sub-Saharan Africa, and equatorial southeast Asia. By 2050, these increases translate into an additional 0·47–0·70 million deaths and Intl$2·40–3·68 billion in annual productivity losses.

Interpretation Rising temperatures are projected to increase the prevalence of physical inactivity, translating into additional premature deaths and productivity losses, especially in tropical regions. Prioritising heat-adaptive urban design, subsidised climate-controlled exercise facilities, and targeted heat-risk communication is essential to mitigate these emerging health and economic burdens, in addition to ambitious emissions reductions.

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Introduction

Physical inactivity represents a major global health challenge. Recent findings indicate that approximately one-third of the global adult population does not adhere to WHO guidelines,[1] which stipulate a minimum of 150 min of moderate intensity or 75 min of vigorous intensity physical activity on a weekly basis.[2] Physical inactivity is one of the leading modifiable risk factors for non-communicable diseases (NCDs) and is responsible for an estimated 5% of all adult deaths,[3] drives US$54 billion in annual direct health-care costs, and generates a further $14 billion in productivity losses.[4] Without decisive action, the global prevalence of physical inactivity could rise, threatening the WHO target of a 15% relative reduction by 2030.[2]

Ambient temperature represents an increasingly crucial environmental determinant of physical activity participation worldwide.[5–7] Heat exposure imposes physiological constraints through elevated cardiovascular strain and heightened perceived exertion, creating substantial barriers to outdoor physical activity.[8] These thermal limitations are compounded by extreme weather events and compromised air quality, which collectively reduce safe opportunities for physical activity—effects that disproportionately impact low-income populations without adequate cooling infrastructure.[9,10] In 2023, global populations experienced an average of 1512 h of ambient conditions posing at least moderate risk of heat stress during light outdoor activity, representing a 28% increase (328 h) above 1990–99 levels.[11]

Climate change might further exacerbate physical inactivity.[12] The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report projects that every additional 0·5°C of global warming will clearly increase the intensity, frequency, and duration of heat–humidity extremes, with labour-productivity losses and health risks.[13] If the world reaches 2°C above preindustrial temperatures, more than a quarter of the global population could experience an extra month of severe heat stress each year relative to the 1950–79 average.[14] Such shifts compress the number of thermally safe hours for exercise, eroding habitual physical activity and

Research in context

Evidence before this study

A comprehensive search was conducted on the PubMed and Scopus databases, encompassing the period from database inception to Feb 28, 2025, combined with the keywords "physical activity", "physical inactivity", or "exercise" with "temperature", "heat", "weather", or "climate", together with the design terms "longitudinal", "panel", "cohort", "time-series", or "cross-section". This strategy identified 35 studies. The available evidence was dominated by short-term weather analyses from high-income settings. To date, only one nationwide study has conducted a cross-sectional smartphone analysis (in 2017), which recorded step counts from nearly 2 million users in the USA. Several investigations in Europe, Australia, and east Asia extended follow-up to a maximum of 5 years; however, none linked long-term heat exposure to physical inactivity across countries. Two systematic reviews reiterated the scarcity of longitudinal research and noted the complete absence of projections based on future climate scenarios. Meanwhile, global burden assessments indicate that physical inactivity already accounts for roughly 5% of adult deaths and incurs about Intl$13·7 billion in productivity losses each year. This limited evidence base hinders policy making aimed at anticipating the health and economic effects of climate change. The present study helps fill this gap by providing a quantitative, longitudinal assessment of the temperature–physical inactivity relationship over more than two decades.

Added value of this study

Our analysis exploits a balanced 156-country panel (2000–22; 3588 observations) that pairs population-weighted temperature distributions with WHO-harmonised inactivity data. By applying a fixed-effects, non-linear bin model and extensive robustness checks, we estimate exposure–response functions: each extra month >27·8°C raises inactivity by 1·44 percentage points globally and 1·85 percentage points in low-income and middle-income countries, with hotspots exceeding 4 percentage points across Central America, the Caribbean, eastern sub-Saharan Africa, and equatorial southeast Asia. Integrating these exposure–response functions with the Coupled Model Intercomparison Project-6 projections yield the first physical inactivity forecasts to 2050, translating projected heat exposure into additional deaths and productivity losses. Our study therefore contributes to the geographical, temporal, and policy evidence that can inform climate-resilient action in global health.

Implications of all the available evidence

Taken together, current evidence and our new findings indicate that rising temperatures will lead to substantial increases in physical inactivity-related health and economic burdens—by 2050 we project 0·47–0·70 million additional premature deaths annually and $2·40–3·68 billion in productivity losses under plausible climate scenarios (SSP1–2.6 to SSP5–8.5), equivalent to 7·19–10·73 percentage points of 2022 physical inactivity-attributable deaths (6·52 million) and 5·12–7·85 percentage points of 2022 physical inactivity productivity losses ($46·92 billion). Heat-responsive urban design, subsidised climate-controlled exercise facilities, and integration of heat risk messaging into physical activity guidelines emerge as immediate adaptation priorities, while ambitious mitigation is essential to avert a heat-driven sedentary transition. Future research should couple subnational accelerometer surveillance with high-resolution climate projections to refine dose–response functions and evaluate the effectiveness of heat-resilient active-mobility infrastructure in real-world settings.

exacerbating inequalities where adaptive capacity is limited. Global evidence on how sustained warming translates into physical inactivity remains scarce, particularly in low-income and middle-income countries (LMICs), where climate-sensitive NCD mortality is already substantial.[15]

The primary objective of this study is to provide a global, data-driven longitudinal assessment of how interannual temperature fluctuations, and their projected future trajectories, affect patterns of physical inactivity. Using country-level data for 156 nations from 2000 to 2022, we proceeded in three steps. First, we estimated an exposure–response function linking temperature distributions to physical inactivity prevalence, accounting for socioeconomic and environmental factors. Second, we combined this exposure–response function with temperature projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) to forecast changes in physical inactivity prevalence by 2050 under three shared socioeconomic pathway (SSP) scenarios (SSP1–2.6, SSP2–4.5, and SSP5–8.5). Third, we translated these forecasts into health and economic burdens through a comparative risk assessment framework, quantifying attributable deaths and productivity losses using a friction-cost approach calibrated to each country's gross domestic product (GDP) and labour participation rates.

Methods

Study design

We conducted a longitudinal panel study to examine the relationship between temperature exposure and physical inactivity across 156 countries from 2000 to 2022. The empirical strategy exploits within-country interannual deviations from each country's long-run mean temperature (ie, years that are slightly warmer or cooler than usual) rather than cross-country differences in average climate. The panel structure allowed us to control for time-invariant country characteristics via country fixed effects, and country-specific time trends account for differential temporal patterns.

The unit of analysis is the country-year; annual temperature exposure and physical inactivity outcomes yield a balanced panel with complete observations for all 156 countries over the 23-year study period (3588 country-years). Inclusion criterion was data completeness for outcomes and covariates after harmonisation; no imputation was required. No a priori sample-size calculation was performed because we analysed the full available universe. The study period was selected to ensure consistency in physical inactivity measurement following the expansion of standardised global surveillance after 2000. This study was not prospectively preregistered; a detailed analysis (including variables, bin definitions, model equation, and robustness checks) is provided in the appendix (pp 4–5), where all model equations are presented. All analyses were conducted using Stata 15.0 (StataCorp, College Station, TX, USA) and R (R Foundation for Statistical Computing, Vienna, Austria).

Outcomes

Our primary outcome was the age-standardised prevalence of physical inactivity among adults (aged ≥18 years), defined as not achieving ≥150 min/week of moderate-intensity activity, ≥75 min/week of vigorous-intensity activity, or an equivalent combination.[2] We extracted sex-specific, country-year series for 2000–22 from the WHO Global Health Observatory harmonised estimates (2024 release); details are provided in the appendix (p 2) and in a previous paper by Strain and colleagues.[1] These estimates are modelled from 507 population-based surveys (approximately 5·7 million participants) using standardised processing of self-reported instruments—principally the Global Physical Activity Questionnaire and the International Physical Activity Questionnaire—and are reported as age-standardised prevalence by sex. We relied on the modelled country-year estimates (Bayesian hierarchical framework) as published by WHO and did not apply additional smoothing or imputation to these series.

Exposures

Our five exposure metrics are country-year temperature intervals (bins) that record the number of months (of 12) with mean temperatures that fall within each bin. We first took the 0·5°×0·5° gridded monthly temperature, aggregated all grid cells lying inside each country, and weighted them with 2010 LandScan population counts available at 0·1°×0·1°. This method yielded monthly temperatures representative of a typical resident. Each month was then assigned to one of the five bins (thresholds were defined using empirical percentiles; appendix p 4); the monthly counts were summed, producing an annual country-level value for every bin. This categorical construction flexibly captured threshold effects, non-linearities, and the asymmetric influence of extreme cold and heat that linear specifications can miss (appendix p 2).

Temperature data were obtained from the Climatic Research Unit Time Series (CRU TS) dataset maintained by the University of East Anglia, UK. This dataset provides comprehensive monthly climate information on a high-resolution 0·5°×0·5° (approximately 50 km) latitude–longitude grid, covering terrestrial areas worldwide. The dataset's global coverage and extensive quality control procedures make it particularly suitable for studies requiring methodological consistency across multiple countries.[16] For instance, the dataset is corrected and adjusted to ensure homogeneity over time, reducing biases associated with changes in weather stations or measurement methodologies.

See Online for appendix

Covariates

We adjusted for a parsimonious set of contemporaneous, time-varying covariates that plausibly confound or covary with temperature and influence physical inactivity. Specifically, we included meteorological dimensions beyond temperature (precipitation, cloud cover, wet days, frost days, and vapour pressure) from CRU TS, and ambient $PM_{2·5}$ from the Atmospheric Composition Analysis Group.[17] All environmental variables were aggregated with 2010 LandScan population weights and aligned to the country-year panel. These factors share upstream climate drivers with temperature, are not consequences of physical inactivity at the annual scale, and their inclusion helps reduce omitted-variable bias and improve precision.[5,18–21] We also adjusted for socioeconomic and health context using GDP per capita and crude death rate (World Bank Open Data; appendix p 3).

Climate change projections

To project future temperature changes, we used data from the CMIP6 multi-model ensemble (multi-model mean) under three scenarios: SSP1–2.6, SSP2–4.5, and SSP5–8.5. Temperature changes by 2050 were estimated by comparing 20-year averages between a historical baseline (1995–2014) and a projected period (2040–59), using high-resolution gridded data (0·25°×0·25°). Country-level estimates were derived by applying 2010 population weights to maintain consistency with the exposure–response estimation. We used the ensemble-all model, which averages outputs across all available climate models, to incorporate uncertainty and provide more robust projections (appendix pp 3, 8).

Statistical analysis

We assessed the effect of climate change and physical inactivity in two steps. First, we estimated the exposure–response function using a binned fixed-effects panel-regression model that allows for flexible, non-linear effects of temperature without imposing a priori functional restrictions—an approach widely used in climate–health studies.[22,23] Monthly mean temperatures were partitioned into five percentile-based bins; for each country-year, we counted the number of months falling in bin j and denoted this variable by $\mathrm{TEM}_{c,t,j}$. The baseline specification is:

$$\mathrm{PI}_{c,t} = \beta_0 + \sum_{j=1}^{5} \theta_j\, \mathrm{TEM}_{c,t,j} + \gamma^{\mathrm{T}}\mathbf{X}_{c,t} + \alpha_c + \phi t_{c,t} + \varepsilon_{c,t}$$

where $\mathrm{PI}_{c,t}$ is the age-standardised prevalence of physical inactivity among adults (aged ≥18 years) in country c and year t. The coefficients θ_j capture the marginal change in physical inactivity associated with 1 additional month in temperature bin j.

$\mathbf{X}_{c,t}$ is a vector of time-varying controls—population-weighted precipitation, cloud cover, frost days, vapour pressure, wet days, $\ln(\mathrm{PM}_{2\cdot5})$, ln(GDP per capita), and the all-cause death rate. Country fixed effects (α_c) absorb time-invariant heterogeneity such as geography or long-standing cultural attitudes towards exercise, and country-specific linear trends ($t_{c,t}$) flexibly capture gradual, idiosyncratic changes (eg, improvements in infrastructure or evolving health awareness). Standard errors were clustered at the country level to allow for serial correlation within countries over time.

Second, we combined the estimated temperature coefficients $\hat{\theta}_j$ with projected shifts in the distribution of monthly mean temperatures under alternative CMIP6 SSP scenarios. Formally, letting $\Delta\mathrm{TEM}_{c,t,j}$ denote the change in the number of months in bin j relative to the historical baseline, the projected change in PI is

$$\Delta\hat{\mathrm{PI}}_{c,t} = \sum_{j=1}^{5} \hat{\theta}_j\, \Delta\mathrm{TEM}_{c,t,j}$$

This two-step framework therefore links observed temperature–physical inactivity relationship to future climate trajectories, providing scenario-specific estimates of the burden of physical inactivity attributable to climate change. This framework is well suited to detect critical behavioural thresholds that would be difficult to uncover with parametric temperature polynomials.[9,24] Finally, to quantify how 2050 temperature increases translate into physical inactivity-related deaths and economic costs, we conducted a health impact assessment with three components. First, we used an exposure–response function (the estimated change in physical inactivity associated with temperature from our fixed-effects model with temperature bins) to obtain temperature-driven shifts in physical inactivity prevalence. Second, we combined this function with temperature projections from the CMIP6, the latest generation of coordinated climate model experiments that inform IPCC assessments, to forecast changes in physical inactivity rates by 2050 under SSP1–2.6, SSP2–4.5, and SSP5–8.5 scenarios. Third, we translated projected physical inactivity increases into attributable deaths (via published relative risks[3] and population-attributable fractions) and into indirect economic costs valued under the friction-cost approach. In the friction-cost approach, productivity losses were limited to the friction period—the average time needed to replace a worker and restore output—rather than the full stream of lifetime earnings (as in the human-capital approach). Accordingly, indirect costs were computed as the product of adult physical inactivity-attributable deaths, the employment-to-population ratio, GDP per employed person (purchasing power parity, constant 2021 prices), and the friction period (appendix p 7). All economic estimates are reported in constant 2021 international dollars.

Sensitivity analyses and robustness checks

To assess the robustness of our estimates, we conducted several checks. First, we ran multiple versions of the regression model: an unadjusted model, a model controlling for fixed effects, a model including fixed effects and climate variables, another that added socioeconomic and health factors, and finally, a fully adjusted model (equation 1). Next, we examined heterogeneity by splitting the sample into LMICs versus high-income countries (HICs) and male versus female. Third, we tested different temperature interval specifications using baseline thresholds (percentile-based) and compared the results against equally spaced bins and bins based on standard deviations to ensure consistency in the results. Fourth, to evaluate whether the global findings were disproportionately driven by any particular region, we applied a leave-one-region-out approach, rerunning the regressions while excluding one region at a time. Finally, we re-estimated the fully adjusted model within terciles of country median age and countries' long-run mean temperature, using country-level means to set cut points.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the manuscript.

Results

The balanced panel comprises 3588 country-year observations covering 156 countries during 2000–22. On average, 25·7% of adults did not achieve the WHO physical activity recommendations (appendix p 9); female individuals are markedly less active than male individuals (29·0% *vs* 22·2%). The population-weighted mean annual temperature was 19·2°C, ranging from sub-zero values in Nordic countries to >28°C in equatorial regions. The IQR of temperatures (12·5–25·8°C) corresponds closely to the middle three percentile-based bins used in the exposure–response analysis, and the two tails (below 4·2°C or above 27·8°C) jointly accounted for 19% of all country-month observations, highlighting the diversity of climatic contexts in the sample. Socioeconomic dispersion was similarly wide; mean

GDP per capita was $12 414 (constant 2015 US$), but spanned an order of magnitude between the bottom and top deciles (appendix p 24). The data suggested a link between climate and physical inactivity; warmer regions (eg, Middle East, south Asia, and Africa) show higher rates of physical inactivity, whereas milder climates (eg, Central Asia and Australia) showed lower rates. Still, the pattern was not uniform—some colder areas such as North America, Argentina, and South Africa also report high rates of physical inactivity.

The highest temperature bin (>27·8°C, 90th percentile) was associated with a significant increase in physical inactivity ($p<0·01$; figure 1). In particular, the fully adjusted model (model 5; appendix p 10) estimated that each additional month with an average temperature above this threshold increased physical inactivity

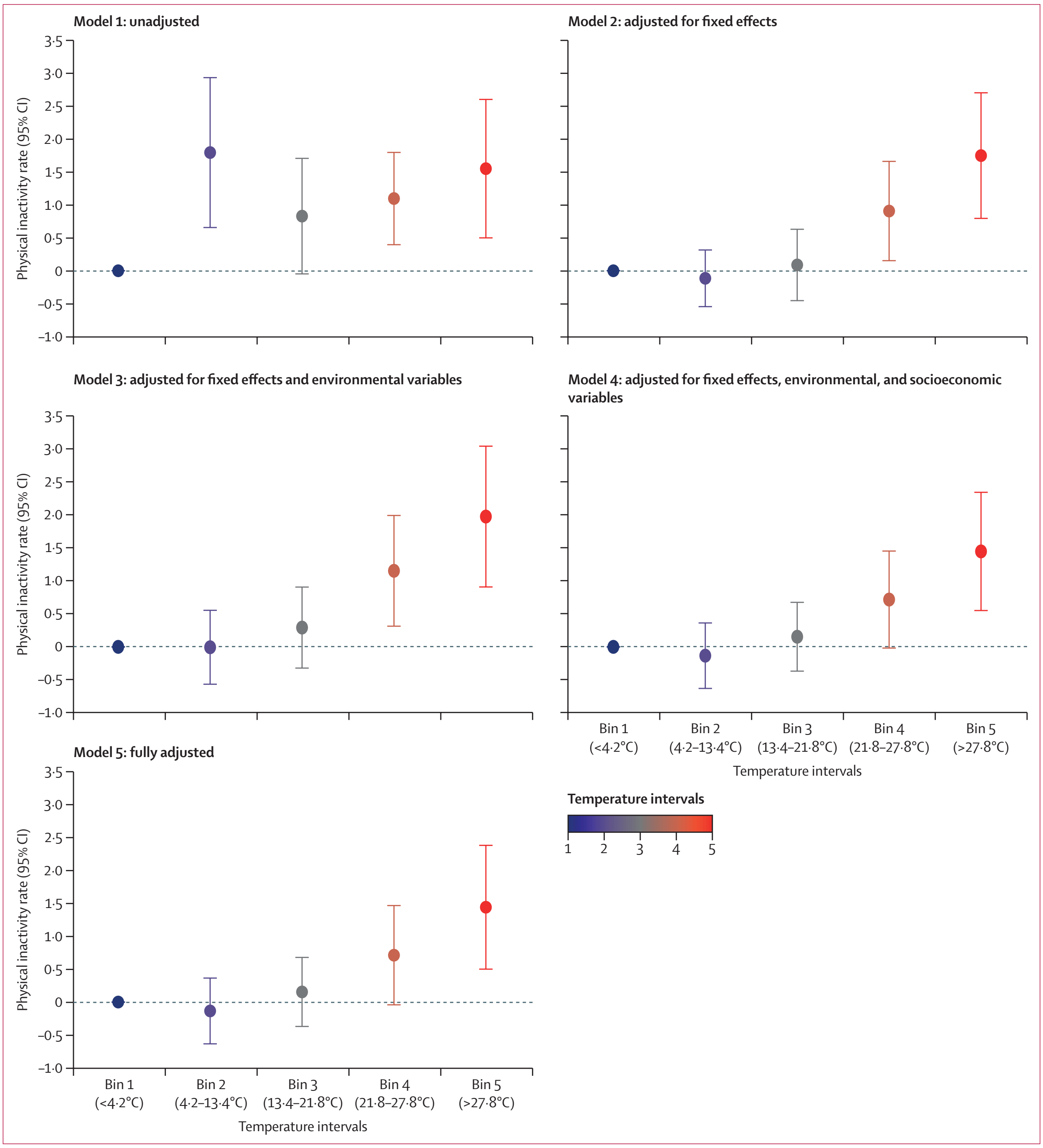


Figure 1: **Effect of population-weighted annual mean temperature on adult physical inactivity prevalence, 156 countries (2000–22)**
The chart reports the estimated marginal effects (percentage-point changes) of five temperature intervals—bin 1 (<4·2°C, reference category), bin 2 (4·2–13·4°C), bin 3 (13·4–21·8°C), bin 4 (21·8–27·8°C), and bin 5 (>27·8°C)—on the prevalence of physical inactivity. Environmental covariates comprise precipitation, vapour pressure, cloud cover, wet days, and $\text{PM}_{2·5}$; socioeconomic covariates comprise GDP per capita and death rate. Error bars indicate 95% CIs.

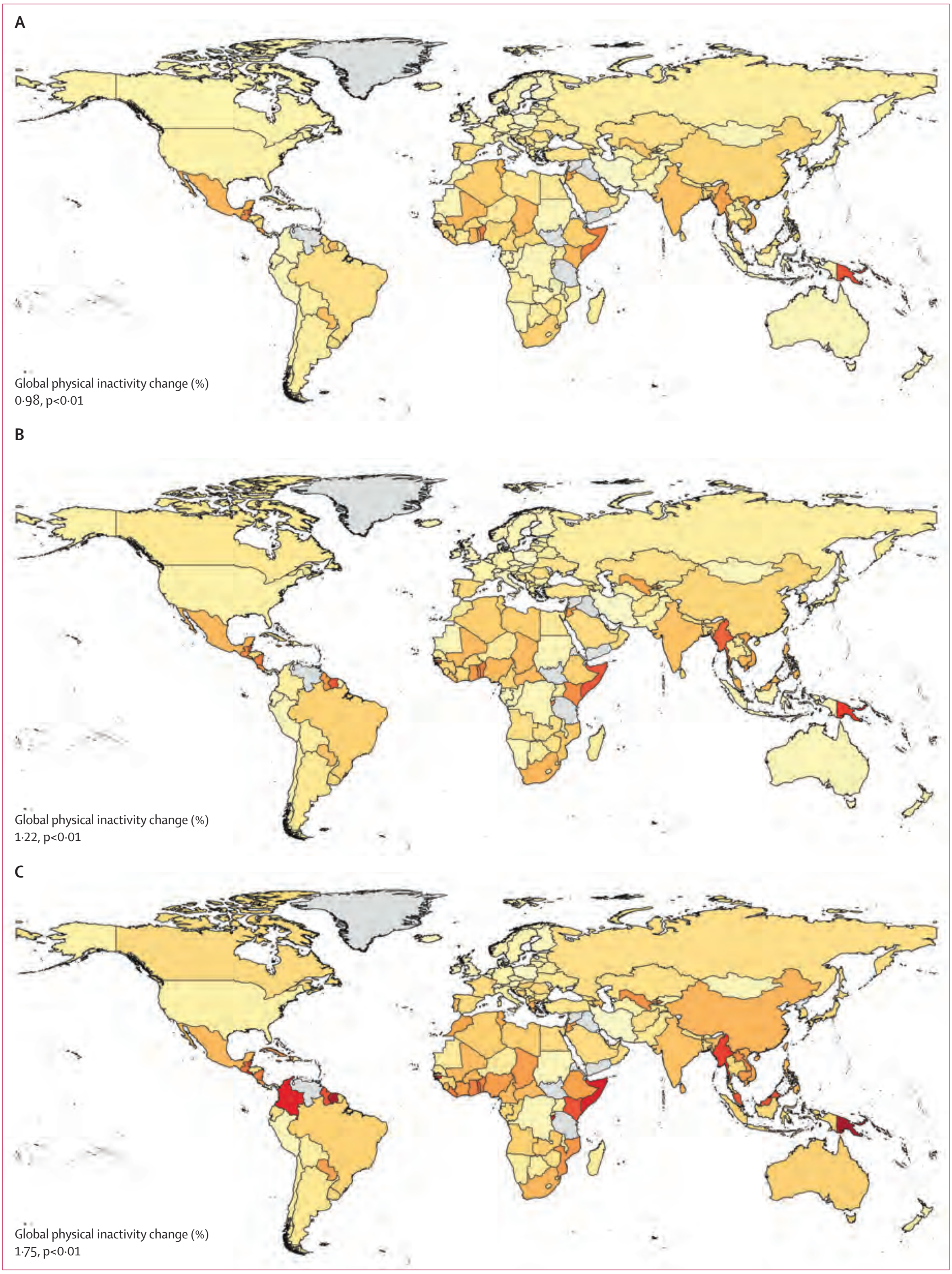


***Figure 2:* Projected country-level change in adult physical inactivity by 2050 under three climate change scenarios**

Maps display the percentage-point change in national physical inactivity prevalence attributable to rising population-weighted mean temperatures between the historical reference period (1995–2014) and 2050 for three different SSPs: SSP1–2.6 (sustainable, low emissions), SSP2–4.5 (intermediate), and SSP5–8.5 (fossil fuel-intensive, high emissions). Colours denote increases in inactivity (0% to >6%), with darker shades indicating larger projected increases. Grey represents countries without data. SSP=shared socioeconomic pathway.

prevalence by 1·44 percentage points (95% CI 0·49–2·39) compared with the baseline temperature of <4·2°C (bin 1, 10th percentile). The coefficients for the second and third bins did not differ significantly from the baseline; the coefficient for the fourth bin was marginally significant (p<0·10). These results remained consistent after accounting for environmental and socioeconomic factors.

Under our main specification (model 5), three patterns stood out. First, for the hottest exposure bin (>27·8°C), the association was stronger among females (1·69 percentage points [95% CI 0·52–2·87]) than among males (1·18 [0·43–1·93]), suggesting greater susceptibility among female individuals to extreme heat (appendix pp 11–12). Second, when stratified by median age (terciles; appendix p 17), bin 5 was significant (p<0·05) only in countries with older populations (tercile three; 2·75 percentage points [0·19–5·30]). Finally, across terciles of countries' long-run mean temperature (tercile one <15·0°C, tercile two 15·0–24·9°C, tercile three ≥24·9°C; appendix p 16), cooler baseline countries (tercile one <15·0°C) showed sizable increases relative to bin 3, the moderate reference range (bin 4: +0·92 percentage points [0·28–1·56]; bin 5: +6·47 percentage points [4·12–8·74]), roughly 4–5 times the magnitude of the pooled bin 5 estimate.

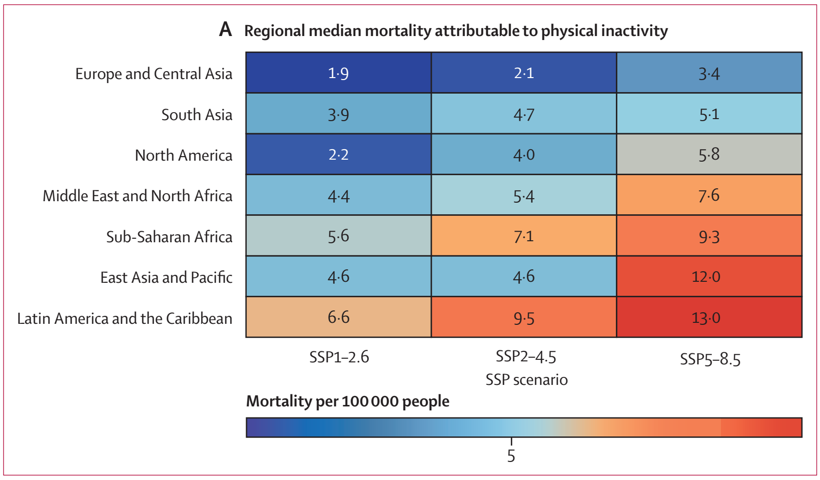
We also estimated exposure coefficients for the fully adjusted model, stratified by income level (appendix p 25). In the HIC model, most temperature bins exhibited only minor deviations from the reference category. In contrast, the LMIC model showed a pronounced increase in physical inactivity at warmer temperatures, highlighting the stronger effect of heat on physical inactivity in these settings. Specifically, the estimated coefficient for temperatures exceeding 27·8°C (bin 5, 90th percentile; appendix p 13) indicates that each additional month within this temperature range would raise physical inactivity prevalence by approximately 1·85 percentage points (95% CI 0·62–3·08).

The results of a sensitivity analysis, in which we systematically excluded one region at a time, are shown in the appendix (p 26). The estimated exposure coefficients, derived from the fully adjusted model (appendix p 14), confirmed the robustness of the temperature–physical inactivity relationship, even when individual regions are omitted. Although some variations in effect sizes were observed, the overall pattern remained unchanged—higher temperatures were consistently associated with increased physical inactivity prevalence. This stability suggests that no single region disproportionately influences the global trend.

The robustness of our findings across different methods of bin construction, including equally spaced intervals and bins defined by standard deviations, is highlighted in the appendix (p 26). An additional month with an average temperature exceeding 37·6°C led to an increase in physical inactivity prevalence of nearly 4·05 percentage points (95% CI 2·81–5·28; appendix p 15). Despite variations in bin definitions, the consistent rise in physical inactivity prevalence at higher temperatures reinforces the strength of our main finding.

Under SSP1–2.6, the global prevalence of physical inactivity is expected to rise by 0·98 percentage points (95% CI 0·47–1·49) by 2050 (appendix p 18). The increase intensifies to 1·22 percentage points (0·58–1·85) in SSP2–4.5 and 1·75 percentage points (0·84–2·66) in SSP5–8.5, all significant at p<0·01. The spatial pattern reveals that these global means mask sharp regional heterogeneity (figure 2); the largest projected jumps (>4 percentage points) cluster in Central America and the Caribbean, eastern sub-Saharan Africa, equatorial southeast Asia, and parts of Oceania, whereas many mid-latitude and high-latitude countries show modest increases (<1 percentage point) or no discernible change. These hotspots coincide with areas experiencing the greatest expansion in months exceeding the 27·8°C threshold identified in our exposure–response model. At the country level, extremes ranged from gains above 5 percentage points in countries such as Belize and Brunei under SSP5–8.5 to virtually no change in nations such as Belgium and Finland under all SSPs (appendix pp 18–23). Overall, these findings indicate that tropical LMICs will experience most of the climate-driven increases in physical inactivity—an early indication that, without more robust mitigation and adaptation, existing health and economic disparities might further intensify.

The projected change in the population-attributable fraction (PAF) of mortality linked to physical inactivity from 2022 to 2050 vary substantially between SSPs (appendix p 27). Under SSP1–2.6, most countries display changes below 1 percentage point; however, as emission trajectories become more carbon-intensive (SSP2–4.5 and especially SSP5–8.5), the PAF rises sharply, exceeding 1·5 percentage points in more than a dozen sub-Saharan African countries and reaching roughly



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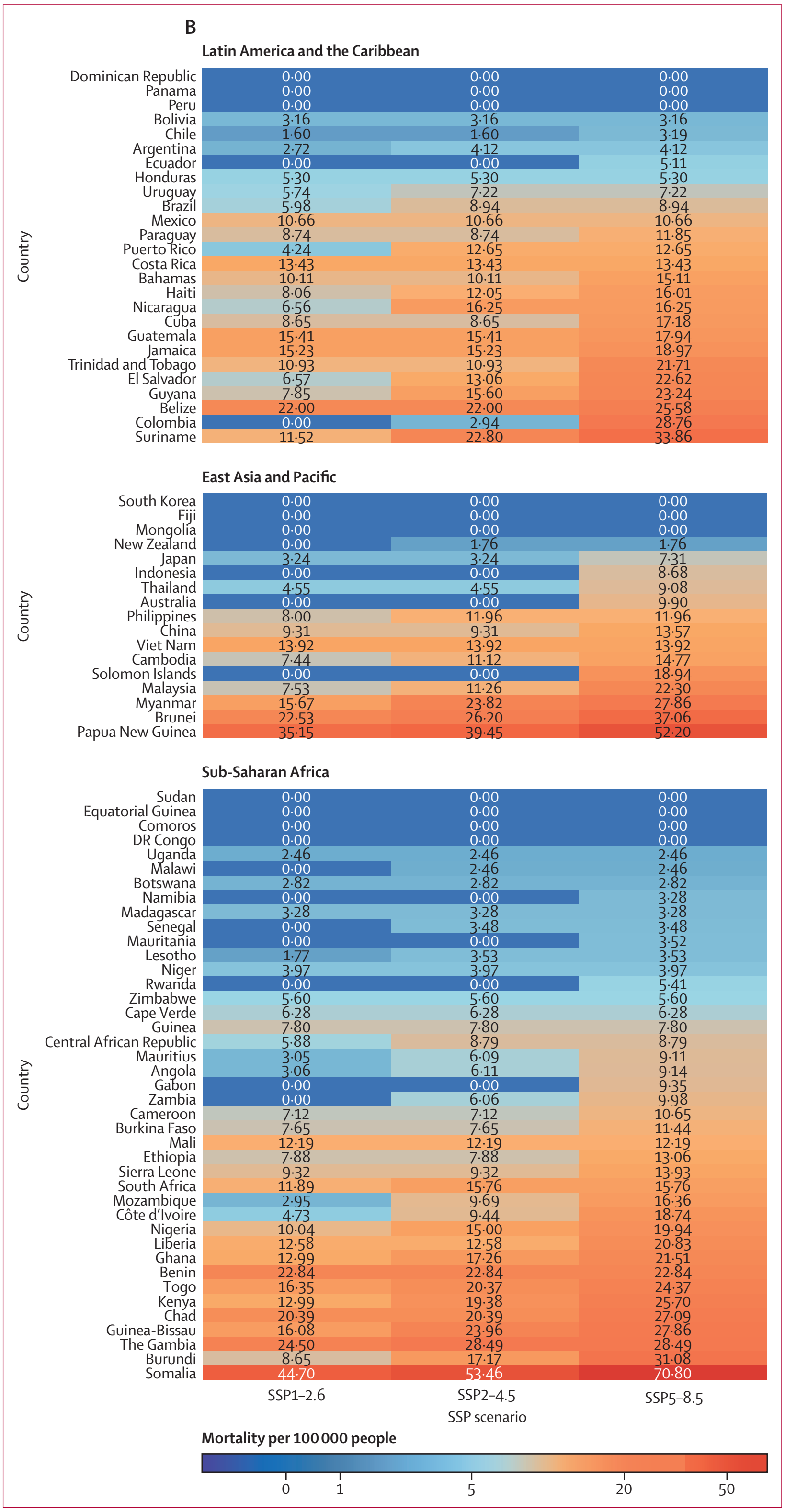

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2 percentage points in several Latin American states (eg, Suriname, Colombia, and El Salvador). The corresponding projections of all-cause mortality attributable to physical inactivity (deaths per 100 000 people) indicate that regional medians remain low across Europe and Central Asia and North America in all scenarios, but increase substantially in sub-Saharan Africa and parts of Latin America and the Caribbean under SSP5–8.5 (figure 3). Furthermore, projections show pronounced within-region variation; in Latin America, for example, Guyana, Nicaragua, and Ecuador show large projected increases—often doubling or more relative to SSP1–2.6.

Per-capita costs by country are shown in the appendix (p 28). Framed against the existing physical inactivity burden, the climate increment is sizable. By 2050, climate-driven physical inactivity is projected to add 0·47–0·70 million deaths per year (7·19–10·73% of 2022 physical inactivity-attributable deaths [6·52 million]) and Intl$2·40–3·68 billion in annual productivity losses, equal to 5·12–7·85% of 2022 physical inactivity productivity losses ($46·92 billion; table). Finally, the global distribution of economic losses is summarised (figure 4). Under SSP5–8.5, middle-income countries bear approximately 54·8% of total losses, with east Asia and Pacific (around 49·5%), followed by Latin America and the Caribbean (around 10·4%) and sub-Saharan Africa (around 6·5%). By contrast, the low-emissions SSP1–2.6 scenario reduces aggregate losses to approximately 65·3% of the SSP5–8.5 scenario, allocating around 15·6% to high-income countries, 30·0% to low-income countries, and 54·5% to middle-income countries.

Discussion

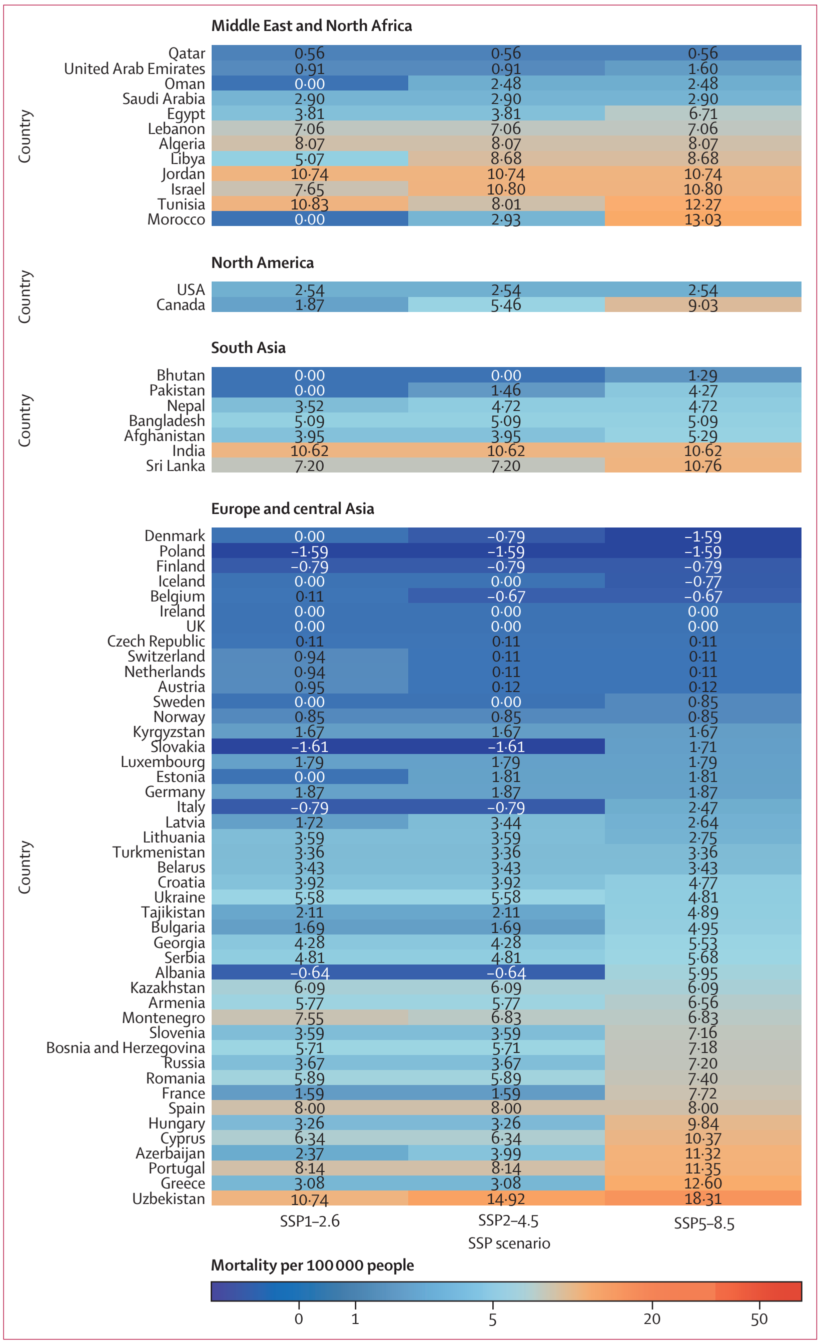
Global evidence indicates that rising temperatures are already associated with lower population-level physical activity, and these effects are projected to intensify with further planetary warming. Using year-to-year temperature fluctuations, we estimated that each additional month with a mean temperature >27·8°C raises adult physical inactivity prevalence by 1·85 percentage points in LMICs but has no discernible effect in HICs. The result is robust to alternative temperature-bin specifications, extensive meteorological and socioeconomic controls, country fixed effects, and country-specific trends. Under the SSP5–8.5 scenario, these effects translate into a projected global increase of 1·75 percentage points in physical inactivity by 2050, with hotspots exceeding 4 percentage points across Central America, the Caribbean, eastern sub-Saharan Africa, and equatorial southeast Asia.

Comparable national studies corroborate the adverse role of heat in physical activity; Obradovich and colleagues[9] documented an inverted-U relationship in the USA with losses on very hot and very cold days. Our multinational estimates likewise show heat-related declines but no measurable penalty from cold, consistent with the thin lower tail of cold exposure across most

LMICs. In high-income settings, where cold exposure is more common, greater adaptation capacity (eg, heating, insulated indoor facilities, appropriate clothing, and substitution towards indoor physical activity) probably dampens any marginal effect on total activity, as corroborated by our income-stratified checks. Moreover, national physical inactivity prevalence estimates are annual country-level averages that do not distinguish physical activity domains (eg, leisure, transport, or occupational); therefore, if cold exposure shifts activity indoors rather than reducing it, domain-specific responses might be offset in the aggregate. Finally, Huang and colleagues[25] linked rising obesity to extreme temperatures and posited heat-induced physical inactivity as a key mechanism, which is supported by our global results.

Several physiological and behavioural pathways plausibly explain the pattern. Heat elevates skin blood flow and sweating, increasing cardiovascular strain, dehydration risk, and perceived exertion; female individuals and older adults, who possess lower evaporative efficiency and sweat rates than males and younger adults, exhibit steeper dose–response slopes in our stratified models.[26] High vapour pressure further impedes evaporative cooling, and concurrent peaks in $PM_{2·5}$ and ozone aggravate respiratory discomfort. The synergy of heat, humidity, and haze probably magnifies avoidance of outdoor movement beyond the main effect captured by our $PM_{2·5}$ control.[27,28] Furthermore, air-conditioned indoor environments provide thermal refuge but often promote sedentary behaviour, reinforcing a feedback loop between heat and physical inactivity.[29]

Because these exposures co-occur disproportionately in tropical LMICs—where air-conditioning penetration, shaded public infrastructure, and discretionary leisure time are scarce—the resulting burden is profoundly inequitable. Outdoor labourers, street vendors, and subsistence farmers cannot easily shift physical exertion to cooler hours; women and adolescents often lack access to climate-controlled recreational spaces; and public health budgets in these settings are least able to absorb downstream cardiometabolic costs.[11] It should be noted that, because our dataset does not disaggregate physical activity by domain, our estimates pertain to total physical activity irrespective of voluntariness. Consequently, cross-setting comparisons where the mix of transport-related and occupation-related physical activity differs should be interpreted with caution—particularly in LMICs, where a substantial share of activity might be non-discretionary.[30]



Middle East and North Africa

Country	SSP1–2.6	SSP2–4.5	SSP5–8.5
Qatar	0·56	0·56	0·56
United Arab Emirates	0·91	0·91	1·60
Oman	0·00	2·48	2·48
Saudi Arabia	2·90	2·90	2·90
Egypt	3·81	3·81	6·71
Lebanon	7·06	7·06	7·06
Algeria	8·07	8·07	8·07
Libya	5·07	8·68	8·68
Jordan	10·74	10·74	10·74
Israel	7·65	10·80	10·80
Tunisia	10·83	8·01	12·27
Morocco	0·00	2·93	13·03

North America

Country	SSP1–2.6	SSP2–4.5	SSP5–8.5
USA	2·54	2·54	2·54
Canada	1·87	5·46	9·03

South Asia

Country	SSP1–2.6	SSP2–4.5	SSP5–8.5
Bhutan	0·00	0·00	1·29
Pakistan	0·00	1·46	4·27
Nepal	3·52	4·72	4·72
Bangladesh	5·09	5·09	5·09
Afghanistan	3·95	3·95	5·29
India	10·62	10·62	10·62
Sri Lanka	7·20	7·20	10·76

Europe and central Asia

Country	SSP1–2.6	SSP2–4.5	SSP5–8.5
Denmark	0·00	–0·79	–1·59
Poland	–1·59	–1·59	–1·59
Finland	–0·79	–0·79	–0·79
Iceland	0·00	0·00	–0·77
Belgium	0·11	–0·67	–0·67
Ireland	0·00	0·00	0·00
UK	0·00	0·00	0·00
Czech Republic	0·11	0·11	0·11
Switzerland	0·94	0·11	0·11
Netherlands	0·94	0·11	0·11
Austria	0·95	0·12	0·12
Sweden	0·00	0·00	0·85
Norway	0·85	0·85	0·85
Kyrgyzstan	1·67	1·67	1·67
Slovakia	–1·61	–1·61	1·71
Luxembourg	1·79	1·79	1·79
Estonia	0·00	1·81	1·81
Germany	1·87	1·87	1·87
Italy	–0·79	–0·79	2·47
Latvia	1·72	3·44	2·64
Lithuania	3·59	3·59	2·75
Turkmenistan	3·36	3·36	3·36
Belarus	3·43	3·43	3·43
Croatia	3·92	3·92	4·77
Ukraine	5·58	5·58	4·81
Tajikistan	2·11	2·11	4·89
Bulgaria	1·69	1·69	4·95
Georgia	4·28	4·28	5·53
Serbia	4·81	4·81	5·68
Albania	–0·64	–0·64	5·95
Kazakhstan	6·09	6·09	6·09
Armenia	5·77	5·77	6·56
Montenegro	7·55	6·83	6·83
Slovenia	3·59	3·59	7·16
Bosnia and Herzegovina	5·71	5·71	7·18
Russia	3·67	3·67	7·20
Romania	5·89	5·89	7·40
France	1·59	1·59	7·72
Spain	8·00	8·00	8·00
Hungary	3·26	3·26	9·84
Cyprus	6·34	6·34	10·37
Azerbaijan	2·37	3·99	11·32
Portugal	8·14	8·14	11·35
Greece	3·08	3·08	12·60
Uzbekistan	10·74	14·92	18·31

Figure 3: **All-cause mortality rates attributable to physical inactivity by country under three 2050 climate change scenarios**

The heat map shows the projected mortality rate attributable to physical inactivity (deaths per 100 000 people) across countries by 2050. Columns correspond to CMIP6 emission pathways (SSP1–2.6, SSP2–4.5, and SSP5–8.5). Projections combine the temperature–physical inactivity dose–response function estimated in this study with SSP-specific population and climate trajectories, holding other risk factors constant. SSP=shared socioeconomic pathway.

Heat-driven physical inactivity also threatens economic output. Reduced muscular strength, impaired cognition, and poor sleep translate into lower on-the-job performance and higher absenteeism.[26,28,29] Benchmarked against direct heat-stress impacts, the International Labour Organization projects that, by 2030, heat stress alone will erase around 2·2% of total working hours worldwide (approximately 80 million full-time jobs), with losses concentrated in agriculture (around 60%) and construction (around 19%) and approaching

	2022	SSP1–2.6	SSP2–4.5	SSP5–8.5
Present and projected deaths (people, millions)	6·52*	0·469	0·521	0·699
Present and projected economic losses (Intl$, billions)	46·92†	2·40	2·59	3·68
Projected *vs* present deaths	NA	7·19%	7·98%	10·73%
Projected *vs* present economic losses	NA	5·12%	5·53%	7·85%
Projected deaths *vs* 2008 baseline‡	NA	8·84%	9·82%	13·20%
Projected economic losses *vs* 2013 baseline†	NA	17·55%	18·93%	26·87%

Totals sum across 149 countries; seven countries were excluded because required economic inputs were unavailable after data harmonisation (North Macedonia, Timor-Leste, Kiribati, Saint Vincent and the Grenadines, São Tomé and Príncipe, Samoa, and Vanuatu). Projected deaths represent additional deaths attributable to climate-driven increases in physical inactivity. Economic losses are valued with the friction-cost method described in the appendix (p 7), which multiplies excess deaths by country-specific employment indicators, gross domestic product per employed person, and a 90-day friction period. Computation of 2022 deaths and 2022 economic losses can be found in the appendix (p 7). NA=not applicable. SSP=shared socioeconomic pathway. *Present deaths are total physical inactivity-attributable deaths, computed as described in the appendix (p 7). †Baseline of Intl$13·7 billion in physical inactivity-productivity losses in 2013.[4] ‡Baseline of 5·3 million physical inactivity-attributable deaths in 2008.[3]

***Table:* Forecast of the additional global health and economic burden attributable to climate-change-induced physical inactivity by 2050**

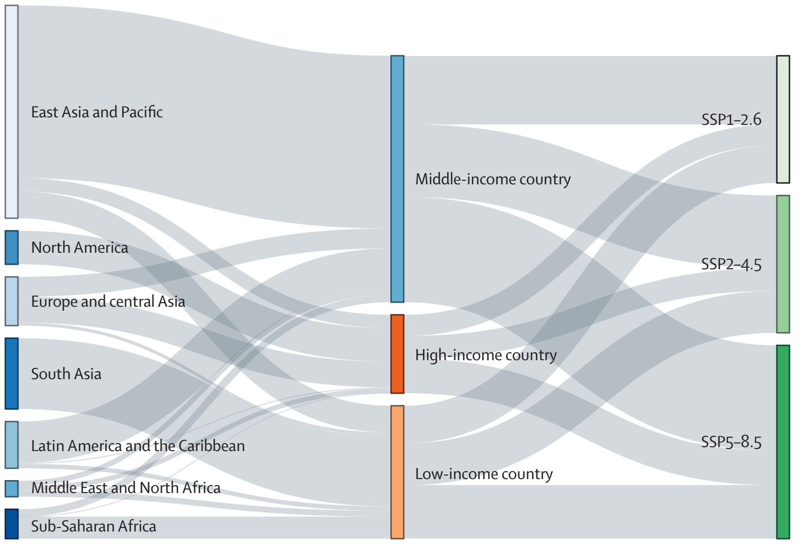


***Figure 4:* Global distribution of physical inactivity costs in 2050 by region, income group, and SSP scenario**
The diagram traces the flow of the economic costs attributable to physical inactivity by 2050 from seven regions, through income categories, to the three CMIP6 emission pathways. Ribbon widths are proportional to each group's share of the global economic burden, and the progressively darker green targets represent higher-emission scenarios that generate larger costs. The visualisation highlights that most losses originate in East Asia and Pacific and other middle-income countries, which together account for over half of total global costs (approximately 55%), with an increasingly large fraction channelled to the high-emissions SSP5–8.5 pathway. Countries without data were excluded. CMIP6=Coupled Model Intercomparison Project Phase 6. SSP=shared socioeconomic pathway.

approximately 5% of working hours in South Asia and Western Africa. Our heat–physical inactivity pathway adds to, rather than replaces, these losses in LMIC hotspots.[31]

When placed within the appropriate context, indirect estimates of productivity-related physical inactivity suggest that climate change could contribute a substantial additional component to the global economic burden. Ding and colleagues[4] estimated physical inactivity-related productivity losses of $13·7 billion in 2013 across 142 countries. Relative to that benchmark, our additional $2·40–3·68 billion projected for 2050 (SSP1–2.6 to SSP5–8.5) corresponds to 17·5–26·9%. Measured against our updated 2022 estimate of current physical inactivity productivity losses ($46·92 billion), the same climate increment amounts to 5·1–7·9%. For mortality, Lee and colleagues[3] reported 5·3 million physical inactivity-attributable deaths in 2008 (versus our present estimate of 6·52 million in 2022); our projected 0·47–0·70 million additional deaths correspond to 8·84–13·20% of that benchmark. These comparisons do not account for differences in country coverage, valuation years, or the macroeconomic series used, but they help place the climate increment in context against established reference points. In summary, unchecked warming threatens to raise the current mortality burden by more than one-tenth and to impose several hundred million dollars in lost labour productivity each year. These costs can be prevented through the implementation of climate-smart physical activity policies.

Interventions that simultaneously cool cities and facilitate movement therefore yield multiple dividends. Expanding connected shade networks, deploying high-reflectance and permeable surfaces, integrating water features, and ensuring access to affordable climate-sheltered public spaces for activity are system-level strategies that lower thermal load and support walking, cycling, and recreation.[25] Beyond heat–comfort gains, such designs can yield co-benefits that standard damage models rarely monetise—mitigating heat-related sleep loss, preserving cognitive performance, and protecting labour productivity—while also addressing inequities in green and blue infrastructure. Finally, if chronic heat contributes to sustained physical inactivity, this might help explain parallel rises in obesity, reinforcing the case for integrated NCD and climate strategies that align urban planning, transport, and public health.[26]

Our findings should be interpreted in light of several limitations. First, the global physical inactivity data rely on 507 population surveys that measured physical activity using self-reported questionnaires rather than accelerometers. Self-report measures introduce recall and social desirability bias, which can dilute temperature–physical inactivity associations and widen uncertainty bounds, particularly in settings where survey instruments or cultural norms differ. Second, the physical inactivity data are only available as annual, national means; therefore, seasonality, subnational heterogeneity, and age-group patterns cannot be explored. The questionnaires also fail to differentiate physical activity domains (eg, leisure, transport, occupational), obscuring behavioural pathways. Third, when constructing climate and air pollution exposures, we used fixed 2010 LandScan population weights to aggregate gridded fields to the country-year level; this maintains comparability across years and scenarios but imposes a time-invariant within-country population distribution, so it does not capture urbanisation or migration over 2000–22, and could attenuate exposure contrasts if populations shift geographically. Fourth, although temperature and $PM_{2\cdot5}$ data are derived from high-resolution grids and then population-aggregated to country-year, socioeconomic and health covariates (eg, GDP per capita and crude death rate) are available only at the country level; this difference in spatial scale could leave residual within-country confounding. Country fixed effects and country-specific trends mitigate, but cannot eliminate, such concerns or the risk of ecological bias. Fifth, we examined only one aspect of climate change—changes in temperature—and did not model other hazards (eg, extreme precipitation, flooding, tropical cyclones, and disaster-related disturbances) that could potentially affect physical inactivity. This decision was due to the lack of comparable data, especially in low-income countries, and the greater uncertainty in future projections about the occurrence and intensity of extreme weather events. Finally, although globally harmonised indicators of green spaces, shade provision, and active transport infrastructure are scarce, our fixed-effects panel regression absorbs much of this unobserved heterogeneity. Temperature coefficients remain virtually unchanged across extensive robustness checks, highlighting the stability and internal validity of our estimates.

Despite these caveats, the implications for global health are immediate. Without stronger mitigation, rising temperatures alone could undermine—or even reverse—a substantial share of WHO's target of cutting global physical inactivity by 15% by 2030,[2] while simultaneously slowing economic growth through heat-related drops in worker productivity. Integrating heat-risk messages into exercise guidelines, directing climate finance towards shade-rich active transport corridors, subsidising cooled exercise facilities for at-risk populations, and enforcing robust occupational heat-safety standards are highly cost-effective actions that deliver concurrent public health, urban liveability, and emissions-reduction benefits. Therefore, treating physical activity as a climate-sensitive necessity—rather than a discretionary lifestyle choice—will be essential to prevent a heat-driven sedentary transition and its accompanying surge in cardiometabolic diseases and economic losses.

Contributors

CG-W and MR conceived the study and developed the overall methodology. CG-W and MR collected, curated, and analysed the data, developed the analytical software, and designed all figures and tables. OM and JHS contributed to the investigation, resources, and validation of results. All authors drafted sections of the manuscript, revised it critically for important intellectual content, had direct access to and verified the underlying data, and approved the final version for publication.

Declaration of interests

We declare no competing interests.

Data sharing

All underlying datasets are publicly available: WHO harmonised physical inactivity dataset (Strain and colleagues;[1] via WHO Global Health Observatory); CRU-TS v4.08 gridded climate observations and CMIP6 model projections (public archives); World Bank World Development Indicators (socioeconomic covariates); and ILOSTAT (labour indicators). The full analysis code is publicly available at https://github.com/garciawitulski/climate-change-PI.git.

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