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Benefit of physical activity initiatives for climate change mitigation and adaptation

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Addressing today's public health challenges requires learning from past successes while adapting to emerging threats. Here we focus on two pressing, interconnected issues: physical inactivity and climate change. We present the Physical Activity and Climate Change (PACC) model, a conceptual framework illustrating how well-designed physical activity initiatives can simultaneously contribute to climate mitigation, support adaptation, and promote health and equity. We provide insights on Indigenous knowledge and contemporary sport, re-imagined urban design, behavioural and equity synergies, and opportunities to develop co-benefit metrics, innovative governance models and cross-sector solutions. We emphasize the need for systems-based, co-designed approaches that prioritize environmental sustainability, health equity and cultural relevance while avoiding unintended consequences. Aligning physical activity and climate change agendas is more powerful than addressing them separately, offering greater combined benefits for population and environmental health. The PACC model offers a practical foundation for advancing integrated, equitable and sustainable solutions.

Nearly four decades ago, the idea of distinguishing between 'sick individuals' and 'sick populations' was first introduced[1]. Since then, applying a population-level lens has enabled major progress in child mortality, infectious diseases, sexually transmitted infections and, more recently, tobacco use, yet the same integrated approach has not been fully applied to some of today's greatest health threats: climate change and physical inactivity.

Plato's quote that "lack of activity destroys the good condition of every human being while movement and methodical physical exercise save it and preserve it" confirms that the notion of health benefits of physical activity is not new, with more rigorous scientific evidence dating back to the 1950s. Despite this, physical activity promotion has largely focused on individual-level determinants with limited progress in addressing the broader systemic, social and environmental factors that drive inactivity[2]. Traditional approaches that address one public health issue at a time are no longer sufficient for ensuring population health and well-being. To contribute to a necessary paradigm shift the physical activity field must: (1) move beyond an individual level focus towards collective, population-wide solutions[3]; (2) centre equity by ensuring that physical activity is a right, not a necessity[4]; and (3) reposition itself as a transdisciplinary and multisectoral societal priority[5].

In contrast, climate change has largely been approached from a population perspective[6]. However, similarly to physical inactivity, the level of attention given to climate change by individuals is not commensurate with the harm it brings. Climate change is already driving substantial health impacts globally[6] with 2024 marking the first year global temperature exceeded 1.5 °C above pre-industrial levels[7]. Vulnerable communities disproportionately face the combined risks of rising temperatures, extreme weather events, forced migration and widening health inequities. Notably, non-communicable conditions linked

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to physical inactivity heighten vulnerability during climate-related events, including heatwaves. Broader societal disruptions, such as conflict, displacement and democratic instability, further affect daily physical activity and well-being.

The intersection of climate change and physical inactivity presents both challenges and opportunities. Rapid, health-centred climate action could deliver direct and indirect health benefits, yet this potential remains underutilized. The World Health Organization Global Action Plan on Physical Activity 2018–2030[8] and the Sustainable Development Goals provide frameworks for aligning these agendas, but integration in research, policy and practice remains limited.

We propose a reconceptualization of the reciprocal relationship between physical activity and climate change, illustrated through a conceptual model (Fig. 1). Four key barriers hinder progress: (1) inequitable impacts on vulnerable populations[6]; (2) unsafe and inequitable access to outdoor environments; (3) misalignment across research, policy and practice; and (4) potential unintended consequences of integration.

This paper highlights practical solutions at the intersection of these agendas, drawing on Indigenous knowledge, sport for development and the co-benefits of integrated action. Through these examples, we demonstrate how a transformative, multisectoral and community-driven approach can advance both population health and environmental sustainability. The key messages of this paper are summarized in Box 1.

Results

The Physical Activity and Climate Change conceptual model

The Physical Activity and Climate Change (PACC) conceptual model (Fig. 1) illustrates dynamic, directional pathways connecting physical activity and climate change. It highlights how physical activity, operationalized through the global framework of the 'eight investments that work for physical activity'[9], can contribute to climate change mitigation by reducing greenhouse gas (GHG) emissions and support climate adaptation and strengthen community resilience by providing infrastructure, programmes and social connections.

The 'eight investments that work for physical activity'[9] span key settings where physical activity promotion has shown evidence-based effectiveness: whole-of-school programmes integrate physical activity opportunities throughout the school day; active transport promotes walking, cycling and public transit for daily travel; active urban design ensures that built environments support movement through accessible infrastructure; healthcare integrates physical activity into healthcare routine practice; public education, including mass media, designed to raise awareness and shape attitudes and norms for being active; sport and recreation for all ensures lifelong and equitable access to recreational opportunities; workplaces support movement into occupational settings; and community-wide programmes engage large populations through coordinated and supportive environments and promote local engagement strategies. These investments are intended to work in combination, creating supportive systems that embed physical activity into everyday life[9] (Table 1).

In the model, the top pathway (the upper circle of the model in Fig. 1) depicts how climate change through extreme weather events, such as heatwaves, air pollution, flooding and storms, can undermine physical activity by making outdoor environments unsafe or inaccessible. Conversely, many physical activity investments, particularly those related to active transport and urban design, can mitigate climate change by reducing reliance on motorized transport and support low-emissions living. However, not all strategies are climate neutral. Some, such as large-scale sport events or energy-intense facilities, may increase emissions, an unintended consequence, highlighting the need for climate-conscious planning. Each investment plays a distinct role, for example: whole-of-school programmes promote safe, active lifestyles and sustainable infrastructure; active transport is the cornerstone of climate mitigation, reducing fossil fuel use and improving air quality;

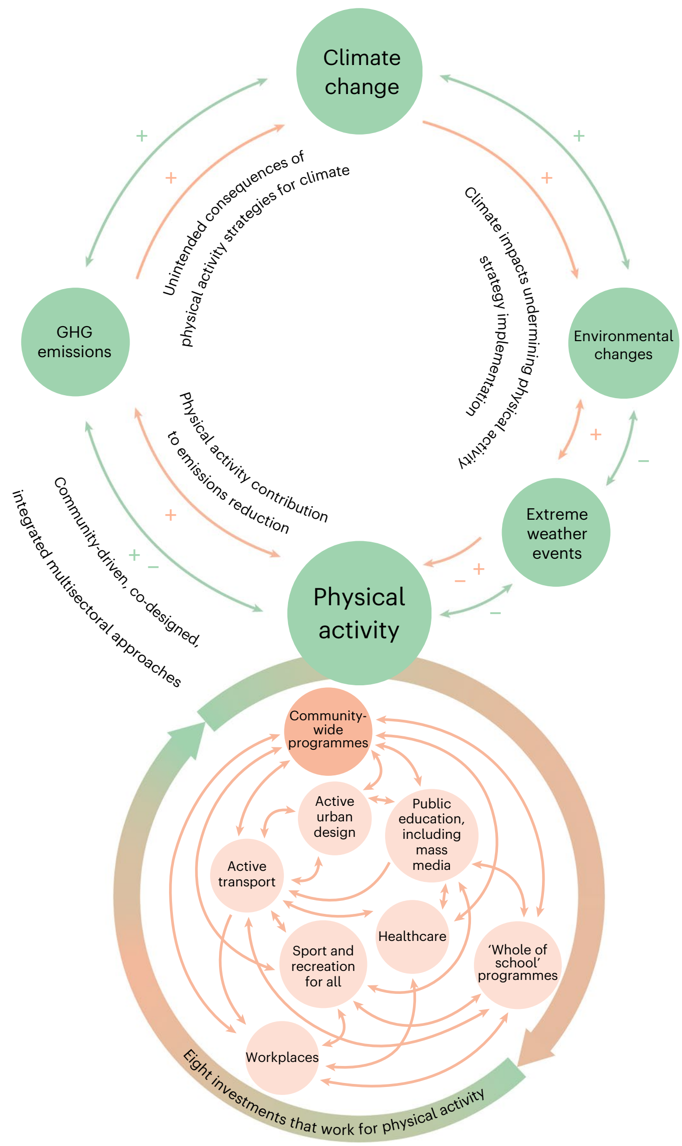

Fig. 1 | The Physical Activity and Climate Change (PACC) conceptual model. Bidirectional arrows indicate synergistic and reciprocal relationships between physical activity and climate change. Green arrows represent mitigation and orange arrows represent adaptation of physical activity solutions to climate change. Green plus symbols represent the impact of physical activity investments on GHG emissions, specifically their role in climate mitigation. For example, active transport reduces car use, lowering emissions. Green minus symbols indicate a harmful or unintended increase in GHG emissions. For example, energy-intensive sports facilities may increase emissions if not sustainably designed. Orange plus symbols illustrate the interaction between physical activity investments and environmental changes as well as extreme weather events. For instance, urban green spaces designed for active living can mitigate urban heat island effects, thereby enhancing climate adaptation and resilience. The orange minus symbols indicate a negative impact or vulnerability to climate change. For example, outdoor physical activity programmes may be disrupted by extreme weather events, such as heatwaves or flooding. Excess GHG emissions drives climate changes that produce multiple types of extreme weather. These climate change impacts and extreme weather events undermine physical activity strategy implementation efforts. Promoting physical activity through the eight strategic investments can contribute to the reduction of GHGs and climate adaptations while improving health outcomes. Multi-sector physical activity interventions can mobilize whole systems and sectors to improve physical activity and environmental sustainability simultaneously. However, with the implementation of the eight strategic investments for physical activity there might be unintended negative consequences to be addressed through integrated and equitable community-driven, co-designed, integrated multisectoral approaches.

BOX 1

Key messages

- The physical activity and climate change agendas intersect through complex, bidirectional and synergistic pathways with a potential contribution towards reducing GHG emissions and physical inactivity, benefiting both human health and environmental sustainability.
- Enhancing evidence-based and scalable physical activity promotion strategies that can contribute to adaptation and mitigation of climate change requires the knowledge residing in Indigenous communities and input from groups most affected, particularly LMIC residents and low-income populations living in HICs.
- The potential benefits of built environment changes on physical activity and active transport are well documented, and we show that such interventions can help reduce GHG emissions. However, we also show a gap in research in LMICs.
- There are encouraging community-driven, physical activity and sport-based solutions that can inform adaptation needs of communities affected or displaced by climate change, but such examples remain underexamined and poorly understood.
- Addressing simultaneously climate impacts and population health through physical activity strategies may bring unintended consequences that can be prevented by systems-focused, community-driven, co-designed solutions centred on environmental sustainability and equity.
- A modal transportation shift towards electric cars could mitigate greenhouse GHG emissions from transportation systems but there are undesirable consequences that need to be addressed to prevent inequitable health and social impacts.
- Climate-sensitive exposures such as extreme heat events may have negative impacts on outdoor physical activity, including active transport, highlighting the need for building liveable, equitable, activity-friendly and climate-resilient cities.
- A collaborative, whole-systems approach within and across sectors can contribute to adapting to and mitigating climate change and improving health through at-scale solutions that work simultaneously for physical activity and climate change global efforts.

active urban design enhances walkability, cycling and green space, reducing car dependency and building climate resilience; healthcare contributes via prevention, potentially lowering healthcare-related emissions; public education, including mass media campaigns, promotes awareness of both health and environmental co-benefits; sport and recreation for all can support low-emission, nature-based activities if planned sustainably; workplaces contribute through active commuting and built environment design; and finally, community-wide programmes refer to local initiatives that engage residents in active living, often with environmental stewardship components (Fig. 1 and Table 1).

The model has four objectives. First, to identify opportunities where physical activity contributes to climate mitigation or adaptation, for example, replacing car trips with walking or cycling, or implementing open streets initiatives. Second, to examine how climate change undermines physical activity such as reduced outdoor activities during extreme heat. Third, to acknowledge that some physical activity interventions may inadvertently contribute to climate change, such as international sporting events[10] or infrastructure development, contributing to GHG emissions[11]. Finally, to recognize unintended consequences, including gentrification and displacement linked to urban redevelopment. Addressing these objectives requires multisectoral, community-led planning[12] to ensure equity and avoid harm[5].

The model was developed through a multidisciplinary group model building process involving experts in physical activity, public health, climate change, system dynamics and participatory modelling. It serves as a systems-level tool for identifying synergies, trade-offs and leverage points, guiding more integrated, equitable and sustainable physical activity investments in a climate-affected world.

To examine the synergistic benefits of physical activity and climate action, we conducted a double scoping review on three built environment exposures, population and/or residential density, land-use mix and streetscape components, linking them to active transport outcomes and GHG emissions (Figs. 2 and 3). Seventy-one studies met inclusion for active transport outcomes, with streetscape components most frequently studied, followed by density and land-use mix. Most studies were conducted at the city or county level, predominantly in the USA and Europe, with limited representation from the global south. Active transport was primarily assessed via walking frequency or amount. In contrast, only 12 studies explored links between built environment and GHG emissions, nearly all conducted in high-income countries (HICs), and most focused on population density. GHG-related outcomes varied but typically included carbon dioxide equivalents or distance travelled metrics.

Together, these findings reveal a geographic and methodological imbalance in the evidence base, highlighting the need for more integrated, quantifiable and equity-sensitive research at the intersection of built environments, mobility and climate outcomes.

Unique opportunities to address the inequitable impacts of climate change and physical inactivity

Public health systems are already under pressure from humanitarian emergencies, some which are aggravated by climate change. An estimated 3.6 billion people already live in areas highly susceptible to adverse impacts of climate change, with low- and middle-income countries (LMICs) and small island developing states disproportionately affected, particularly where medical and public health systems are fragile[6]. Within countries, the most affected groups include Indigenous populations, women, children, older adults, ethnic minorities, economically disadvantaged communities, migrants, refugees and individuals with underlying health conditions[6]. Climate migration is on the rise, with projections suggesting that at the current pace, over 216 million people will be displaced within their own countries by 2050[6], further increasing demands on already strained public health systems[13].

Importantly, the populations most affected by climate change are often those experiencing higher levels of physical inactivity during leisure time and the least able to protect themselves from climate impacts. Recent findings indicate that adults are less physically active in extreme weather conditions[6,13]. Hence, physical activity promotion strategies face the dual challenge of mitigating climate change impacts while enhancing the resilience of vulnerable populations to safeguard their health and uphold their ability and right to be physically active as the climate changes.

The rapid response and adaptation needed to enhance widespread implementation of evidence-based physical activity promotion could be informed by community-driven, bottom-up solutions, with particular emphasis on Indigenous communities who have demonstrated resilience through generations of environmental change, economic hardship and conflict[14]. Sport for development also offers a promising avenue to build resilience, skills and hope within communities. For example, two Indigenous case studies from Māori people of Aotearoa New Zealand (vulnerable population within an HIC) and Turkana people (vulnerable people within an LMIC), and the role of Sport For Development and Peace (SFDP) are highlighted in Box 2.

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Table 1 | Eight investment strategies that work for physical activity (alphabetically) and their relationship to climate change

Investment strategy and description	Sectors involved	Climate change tactic	Amplifies climate change	Vulnerable to climate change	Adapts to climate change	Mitigates climate change
(1) Active transport: promotion of initiatives such as walking and cycling for daily travel	Transportation, planning	Promote walking, cycling and public transit to reduce fossil fuel use	Demand for cars and car infrastructure	Infrastructure for walking and cycling	Resilient walking/cycling infrastructure	Investment in active/public transport
(2) Active urban design: built environments support movement through accessible infrastructure	Planning, transportation	(Re)design cities to support active travel and green space	Prioritizing car infrastructure	Active travel and public spaces	Green spaces and proximity to homes	Reliable public transit and green space
(3) Community-wide programmes: coordinated approach to create supportive environments and promote local engagement	All	Engage residents in active living and environmental stewardship	Unsustainable events and facilities	Community access and facilities	Climate-resilient community interventions	Promoting active transport and infrastructure advocacy
(4) Healthcare: integration of physical activity into healthcare practice where health professionals assess and advise on physical activity as part of routine care	Health	Integrate physical activity into clinical care to reduce emissions through prevention	Healthcare facilities and infrastructure	Healthcare workers and facilities	Physical activity facilities as emergency shelters	Physical activity in primary care for prevention
(5) Public education, media and communications: raise awareness and shape attitudes towards being active	Health, transportation, education, others	Raise awareness of health and environmental physical activity benefits	Campaigns ignoring sustainability	Access to communication channels	Physical activity curricula include climate topics	Media partnerships with climate groups
(6) Sport and recreation for all: ensures equitable access to recreational opportunities across the life course	Sport and recreation	Ensure equitable access to physical activity in nature-based settings	Travel to sports events	Sporting events and infrastructure	Modifying sport infrastructure	Sustainable practices in sport events
(7) Whole-of-school programmes: embed physical activity opportunities throughout the school day	Education	Encourage active lifestyles in children with safe travel to school	School physical activity infrastructure emissions	School environments for physical activity	Resilient school facilities and routes	Quality environments for active transport and physical activity
(8) Workplaces: initiatives that embed physical activity into occupational settings	Employers from all sectors	Promote active commuting and movement-friendly workplaces	Unsustainable workplace practices	Outdoor industries and workers	Workplace wellness and resilience	Active commuting and infrastructure

Definitions, sectors involved, tactics and examples that amplify, are vulnerable to, adapt to and mitigate the effects of climate change

While these case studies are encouraging, they remain rare and are often unevaluated. With an increasing number of people severely affected by climate change, resources should be allocated to monitor and evaluate outcomes for both physical activity and climate. Indigenous knowledge and contemporary sports culture can be used as vehicles to address some of the adaptation needs of communities affected or displaced by climate change to participate in physical activity, while building skills, resilience and capacity in climate change action[15]. Notably, some physical activity interventions also contribute to humanitarian, development and peace outcomes, demonstrating synergy across several Sustainable Development Goals[11].

Reclaiming the outdoors safely and sustainably in the changing climate

Extreme heat increases morbidity, exacerbates health conditions, and raises the risk of heat stress and heat stroke[16]. This risk is further compounded by the danger of outdoor physical activity in extreme heat. The 2023 Lancet Countdown[17] reports that, compared with the period of 1991–2000, the period of 2013–2022 saw a record high of 27.7% more annual hours of ambient heat, posing a moderate-to-high risk of heat stress for those undertaking light and moderate intensity outdoor physical activity.

Extreme heat and other weather extremes are already reducing physical activity levels. Effective and sustainable adaptations are urgently needed to ensure that physical activity remains safe, equitable and accessible, whether out of necessity[4], such as outdoor work or active transport, or by choice, such as sport and recreation. Using a case study from Denver, Colorado, USA, as an example, we show how time-series data might be used to examine the relationship between a climate factor (that is, days >37.7 °C/100 °F) and a physical activity metric (cycling) (Methods).

A plot of daily bicycle distance ridden is presented in Fig. 4a. Figure 4b shows daily bicycle distance ridden with temperature, and the blue points denote days with temperatures above 100 °F. As the figure illustrates, the maximum temperature is not strongly associated with the distance ridden on bicycles. To inform the predictive model, we present the average daily maximum temperature by day of week and month in Fig. 4c,d, respectively. In Fig. 4d, the predicted daily value of bicycle distance ridden and its 95% confidence interval (CI) is plotted against the corresponding observed value for that day. Note that this figure includes all days, including treatment days. The predicted values on the treatment days are out-of-sample (counterfactual) predictions, while those for the control days are in-sample predictions. For those days with points, if the predicted value exceeds the observed value, the

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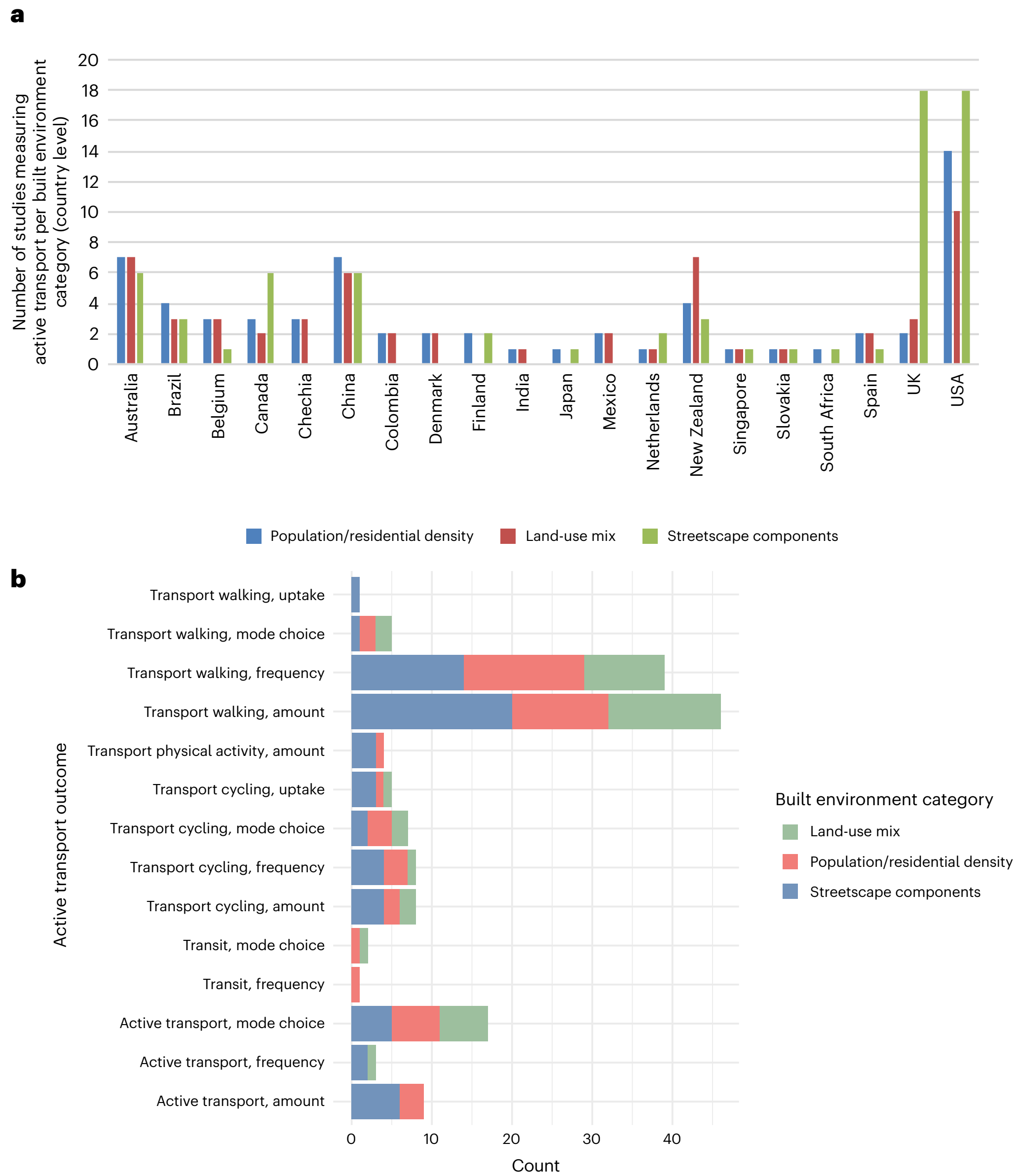

Fig. 2 | Studies reporting associations between built environment characteristics and active transport outcomes. a, Summary and types of outcome: population and/or residential density, land-use mix, and streetscape design to support physical activity. We describe the spatial distribution of studies that investigated the effects of the three built environment exposures of interest on active transportation outcomes. We observe an important geographical heterogeneity as the vast majority of studies were conducted in HICs. Global distribution was stratified by built environment exposures and revealed the same pattern. We note that only two studies were conducted in Africa, which highlights the pressing need to conduct more research to document such links in diverse urban contexts among understudied communities. **b**, Summary of types of active transport outcome: in relation to land-use mix, population and/or residential density, and streetscape design, we summarize the types of active transport outcome that have been investigated. We found an important diversity in active transportation outcomes, with most studies considering walking frequency or duration. Fewer studies considered bicycling or composite transit mode indicators such as mode choice. Structural built environment interventions can substantially improve active transportation behaviours in urban contexts[17]. Yet, such evidence is concentrated among HICs and communities.

effect point estimate is positive. If the predicted value is less than the observed value, the effect point estimate is negative.

The estimated ratio effect of the extreme-heat days on bicycling during those days is 0.95 (95% CI, (0.87, 1.05)), and the estimated difference effect is −1,478 bicycle-kilometres ridden (95% CI, (−4,186, 1,360)). Considering that a large share of the CIs are on each side of the null, we interpret these effect estimates as essentially null, although the point estimates indicate small negative effects. We recognize that this finding is counterintuitive and requires interpretation. Typically, Strava users are serious exercisers who adapt by shifting their training to cooler times of day, rather than reducing activity. As the heatwave was defined by peak temperature, this likely explains the stable activity levels observed. However, these users are not representative of the general population, who are more likely to reduce outdoor activity in extreme heat. It is important to clarify that this finding does not suggest that heat has no impact, but rather reflects behavioural adaptation among a specific, motivated subgroup. We presented this case study as an example to show how time-series data might be used to examine the relationship between physical activity and a climate factor.

To create climate-resilient physical activity opportunities, co-designed, locally relevant interventions are essential. For example, leisure-time activity requires shading, safe drinking water, and suitable

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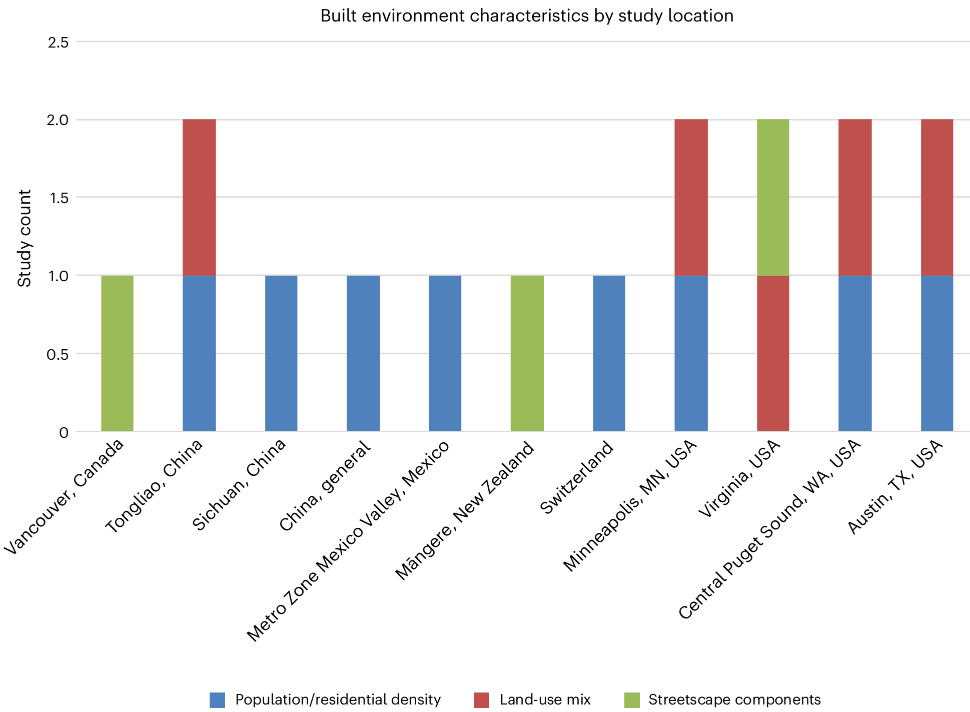

Fig. 3 | GHG studies in relation to built environment features around the world. Spatial distribution of all included studies on built environments and active transport that quantify the potential benefits for GHG emissions. Included studies considered GHG emissions indicators such as vehicle miles travelled, travel distance, speed, carbon dioxide emissions or change in motor vehicle speed/volume. Studies were located in the USA, China, New Zealand[51], Switzerland and Mexico. Available evidence related to positive effects of the selected built environment exposures on GHGs was limited compared with active transportation outcomes. Of interest are the diversity of GHG indicators that have been studied and only one study considered rural villages. Apart from one study, all identified studies were conducted in the past 10 years, indicating that this constitutes an emerging field of research.

clothing and equipment. For those undertaking necessity-based activity[4], such as work or transport, health, safety and comfort must be prioritized. Adaptations for outdoor workers include shifting work hours, providing shade, ensuring hydration and using ventilated clothing. Active transport infrastructure should incorporate shade, shelters and drinking fountains with expanded public transit, particularly in disadvantaged communities.

Promoting outdoor activities even in hot weather means creating climate-responsive urban design and landscaping principles as well as building codes for designing cities and neighbourhoods to prevent urban heat island effects. Blue and green infrastructure—bodies of water, vegetation, parks and rooftop gardens—help to regulate urban microclimates and provide environmental, health and social benefits[18]. Yet, access to greenery remains unequal, often mirroring broader social inequities. Promising examples such as Singapore's Marina Barrage demonstrate how climate adaptation can deliver co-benefits for health, activity and equity. Blue and green infrastructures need to be integrated with mixed land use and active transport networks to ensure equitable access across cities and towns[19].

Relying solely on air-conditioned indoor spaces as an adaptation strategy risks worsening GHG emissions, overwhelming energy grids and increasing inequalities. Instead, sustainable urban design, equitable green space access and climate-resilient infrastructure are key to reclaiming the outdoors. As a species, humans need interactions with the outdoors to survive and thrive. Spending time outdoors affects health and well-being in myriad pathways[20], and time in nature can also be harnessed as unique teaching moments, to facilitate learning, deepen a connection with nature and promote pro-environment behaviours.

Re-imagining policies and strategies for physical activity and climate change action

Advances in the physical activity policy landscape, both globally and locally, have been documented[21]. However, implementation and evaluation of the policies remain a challenge as examined in depth in ref. 22. Similarly, climate change global, regional and local policies have advanced recently, and although implementation efforts have been somewhat successful[6], the scale and sustainability of such efforts are still not commensurate to the urgency[6]. There may be value in reimagining how to align climate change and physical activity research[2], policy and practice agendas to improve both categories of outcomes.

Integrating policies on climate change adaptation and mitigation and physical activity could help address some of the barriers to advancing actions on both arenas[23]. The multiple co-benefits shared by physical activity and climate change policies could be emphasized and demonstrated to generate political support for an integrated approach. For instance, a recent survey showed that most adults living in Canada support policies that align with the recommended policy actions related to physical activity and climate change[24]. Advancing physical activity policies with clearly stated co-benefits for climate could help enhance the attractiveness of integrating climate policy ambitions and actions in sectoral objectives and actions[23]. This approach has the potential to facilitate physical activity policy action by harnessing physical activity advocacy to rapidly advance climate action by highlighting the dual benefits of increased physical activity and climate action[19]. Establishing metrics and indicators to evaluate the effectiveness of implementing integrated policies[25] in promoting physical activity[2] and reducing GHG emissions could also benefit both agendas. For instance, existing and new physical activity and climate-related surveillance systems[26] could benefit from identifying climate impacts and assessing common vulnerabilities using tools that are available but not yet integrated (for example, satellite imaging and remote sensing, climate models and simulation tools, carbon footprint calculators, and health impact assessments). It would be valuable to assess public support for policies designed to have both climate and physical activity benefits, compared with single-focus policies.

BOX 2

Indigenous and community-driven pathways to address climate and physical activity inequities

The importance of Indigenous ancestral knowledge to address the inequitable impacts of climate change and physical inactivity. There is the belief that Māori people of Aotearoa New Zealand share ancestry (whakapapa) with all aspects of the environment and therefore a genetic connection with the environment as one family (whānau)[43]. Oneness with the environment is reflected in the Māori Health and Wellbeing Model[52], and the Atua Matua Māori Health Framework (https://sportnz.org.nz/media/2229/atua_matua_framework_dr-ihirangi-heke.pdf), highlighting the connection between environment and humans through Mātauranga (Māori ancestral knowledge) where physical activity and health are incidental outcomes. While Māori treasure, protect and guard the natural environment (kaitiakitanga), as family would protect their members, unchecked human consumption has resulted in the climate effects that affect Māori people disproportionately[53]. For example, approximately 80% of Māori land is in areas susceptible to erosion, which is expected to disrupt traditional practices such as Marae[54] convening (traditional gathering place) where customs, cultural festivals and sporting events take place.

Despite these challenges, Māori communities can be an exemplar of adapting traditional practice to address contemporary challenges posed by climate change. This is done primarily through incorporating Mātauranga (ancestral wisdom/knowledge) in modern physical activity programmes to promote climate resilience and sustainability. For example, the Atua Matua Health Framework is implemented at Toi Tangata (Māori Health Promoting community organization, https://toitangata.co.nz/), among other initiatives that help families engage in developing knowledge through connection to the natural environment and physical activity[55]. Another notable example is the leadership from Māori research organizations to provide guidance on projected impacts of climate change on Māori communities; suggested adaptation strategies include a focus on physical activity[56]. Other examples include the establishment of partnerships and collaborations between Māori communities and governmental organizations to develop climate-resilient strategies[56]. A key component in these collaborations is respecting and valuing Indigenous knowledge so that solutions are realistic, relevant and sustainable for the communities they are designed to serve[56].

Similarly, the Turkana tribe of Kenya, who are semi-nomadic and nomadic pastoralists, have a close connection to the land. For many centuries their lives were guided by the alternating wet and dry seasons, which determined the cycle of nomadic movements covering several kilometres in search of pasture. Climate change has resulted in drought, reduced water sources and dwindling pastures with severe adverse impacts on Turkana land[57]. These changes impacted Turkana livelihood and food security due to livestock losses, and have contributed to the emergence of a sedentary lifestyle and sourcing of alternative livelihoods among the Turkana especially in urban areas. Turkana people use a variety of coping and adaptation strategies to overcome the impacts of drought including, among others, the mobilization of livestock to track forage and water resources and sending children to school for formal education as a long-term investment.

Recently, a climate change adaptation action plan was developed for the Turkana West subregion, informed by community members including the area chief, elders and committee members and involving a diverse group of men, women, youth, elders and people living with disabilities. Young people in Africa have advocated for change to address climate. One notable example was the 2015 campaign led by Turkana youth to plant thousands of Indigenous and exotic trees in their villages, culminating with a 2024 announcement by the Turkana County Government and the Turkana Girl Child Network Organisation (https://www.kenyanews.go.ke/county-turkana-girl-child-network-organisation-to-plant-1-2-million-trees-annually/) to plant 1.2 million trees with the allocation of financial resources to achieve 30% tree cover in Turkana by 2032.

The power of sport for development to address inequitable impact of climate change and physical inactivity on vulnerable communities. Sport is affected by climate change, through heat and extreme weather events[11]. Yet, sport as a sector, particularly professional sport, can have a substantial carbon footprint[10]. For example, major sporting events, such as the Olympics and the FIFA World Cup, require the international movement of thousands of participants and spectators[58]. To address this, the United Nations launched the Sports for Climate Initiatives and urged global sporting organizations to halve emissions by 2030 and aim for net-zero emissions by 2040 (https://www.un.org/en/observances/sport-day). Many sport organizations, such as the International Olympic Committee and FIFA, have joined the United Nation's 'Race to Zero' campaign.

A particular area of sport relevant for combatting climate change is Sport For Development and Peace (SFDP). The United Nations now explicitly recognizes sport as an enabler of sustainable development and an important player in climate change mitigation. SFDP is a promising avenue for protecting the health and well-being of populations who are vulnerable to climate change[59]. Initiatives are now being implemented around the globe using SFDP for building community resilience and improving mental and social well-being within the context of climate change and population displacement.

One example is, the Olympic Refugee Foundation-funded SPIRIT (Sport for Protection, Resilience, and Transformation) programme, which helped young displaced people build resilience and overcome environmental challenges in the slums in Dhaka, Bangladesh, where a large number of people displaced by climate change-related impacts reside. In Cairo, Egypt, a UEFA (Union of European Football Associations) Foundation for Children-funded programme, Football for Climate Change, used football to promote social cohesion among vulnerable Egyptians and refugees living in Egypt, home to 290,000 registered refugees and asylum seekers. In addition to addressing skills important to young people, such as leadership and community engagement, this programme encouraged young people to take action on climate change.

Culturally grounded sporting initiatives also demonstrate the potential of sport to advance climate and health goals, particularly for Indigenous and marginalized communities. In Aotearoa New Zealand, Waka Ama (outrigger canoeing) and Iron Māori exemplify how culturally relevant sports can simultaneously promote physical activity, strengthen cultural identity and enable a deeper connection with the natural environment. These initiatives reinforce the shared goals of climate action, community health and well-being, while respecting Indigenous knowledge and values.

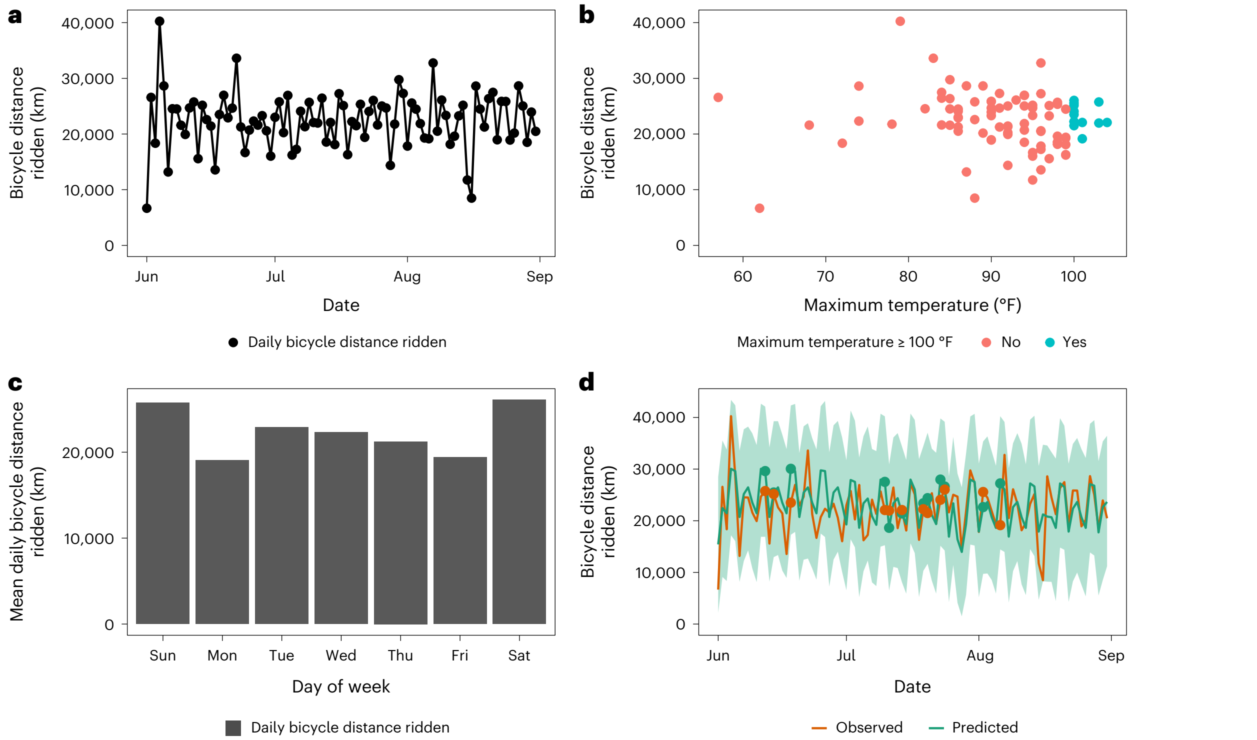

Fig. 4 | Case study example showing time-series data used to examine the relationship between a climate factor and physical activity. a, Plot of daily bicycle distance ridden as reported by Strava Metro data over time in Denver, Colorado, USA, between 1 June 2022 and 31 August 2022. Source: Strava Metro 2022. **b**, Plot of daily bicycle distance ridden as reported by Strava and daily maximum temperature, where the blue dots are those days with a maximum temperature of 100 °F or greater. Source: Strava Metro 2022. **c**, Mean daily bicycle distance ridden by day of week. Source: Strava Metro 2022. **d**, Observed versus predicted bicycle distance ridden. The points denote those days with a maximum temperature of 100 °F or greater. Control days do not have points. The shaded region is the 95% CI of the predicted bicycle distance on that day.

Addressing unintended consequences

Integrated solutions for climate action and population health can deliver substantial benefits but may also bring unintended consequences such as the worsening of social inequities if not carefully designed, as examined in ref. 27. To prevent rising of inequities, solutions need to be systems focused, community driven, co-designed and centred on environmental sustainability. We present two examples.

Liveable cities for health and sustainability. Prioritizing health and well-being alongside climate action requires aligning emissions reduction with active-living initiatives. In established cities, this means increasing housing density and enhancing infrastructure for active and public transport. In rapidly growing cities, liveable, compact neighbourhoods characterized by high residential density[28] mixed land use[29], good street connectivity[28], and infrastructure that encourages walking and cycling[29] can reduce car dependence and GHG emissions. Compact neighbourhoods' physical distances[30] for employment[31], essential services, parks[30] and recreational facilities is minimized, making active travel more feasible and attractive. However, while compact development can reduce car dependence[30] and subsequently GHG emissions, it inadvertently may drive gentrification, raising housing prices and displacing long-time residents to areas with fewer services (for example, access to healthy food, healthcare, education) and opportunities for physical activity. Even without displacement, rising costs and changing neighbourhood character can breakdown vital social networks. Singapore offers a compelling example of how inclusive policies, such as the Ethnic Integration Policy[32] and widespread public housing development, can support social mixing across income and ethnic groups within high-density environments. To minimize unintended consequences, public participation and community-driven approaches are key to prioritizing, enacting and monitoring policies that encourage resident retention and reinforce community identity[12]. Housing policies, for instance, rent-to-buy schemes and subsidies, can support retention. Cross-sector collaboration among climate, urban planning and health sectors is needed to integrate climate-responsive design into land-use and transport policies.

Transport solutions beyond electric cars. While electric cars can reduce GHG emissions and air pollution, they carry environmental, social economic and health trade-offs. Most electric car production relies on fossil fuels, and battery manufacturing requires resource-intensive mining with ethical concerns. In addition, government subsidies promoting electric vehicles purchasing tend to benefit the more affluent segments of society, as electric cars remain unaffordable to many. Replacing fossil fuel cars one-to-one with electric cars does not address urban congestion, physical inactivity or inequities in transport access.

A shift towards active and public transport offers greater co-benefits for health, climate and equity that may also result in substantial economic savings for governments. However, there remains debate over the extent to which investments in walking and cycling infrastructure alone materially reduce GHG emissions, as shown by simulation[33], particularly when broader systemic factors, such as energy sources, land use and travel behaviour, are considered. This tension highlights a critical area for further research: understanding the specific conditions under which active transport investments yield substantial climate benefits, and how these can be optimized across diverse urban contexts. In addition, over-dependence on active travel can exclude older adults or those who are physically disabled, or those in areas with inadequate infrastructure.

Community engagement is essential to ensure that transport investments meet local needs and avoid unintended harms.

Collaboration among diverse sectors such as government, transport, city planning, education, businesses, media and community organizations, with the inclusion of public health professionals, is essential[12]. Such collaborations can drive investments in active transport and public transit that sustainably prioritize human health and well-being[19]. This highlights the urgency of policies that prioritize investment in resilient and carbon-neutral active transport and public transit over car infrastructure. Such prioritization requires the political will to allocate a substantial part of national, federal, state or regional budgets to the long-term development and sustainability of quality active transport and public transit infrastructure. Putting communities at the centre of decision-making promotes ownership, guardianship and social cohesion, the foundation for lasting, sustainable change.

Discussion

Tackling the dual crises of climate change and declining population health requires scalable, evidence-based strategies that deliver cross-sectoral co-benefits[34]. The PACC conceptual model developed in this paper shows how the 'eight best investment strategies for promoting physical activity'[9] can contribute not only to increasing physical activity but also simultaneously to reducing GHG emissions, enhancing community resilience and protecting those most vulnerable to climate-related health risks.

These strategies also align with broader Sustainable Development Goals[11]. For example, transitioning rapidly to clean, renewable energy could prevent the majority of anthropogenic emissions while also avoiding an estimated 5 million deaths annually from air pollution linked to fossil fuel use[35]. Similarly, people-centred urban design that prioritizes safe public transport, active travel, and access to green and blue spaces[36] can reduce both GHG emissions and the estimated 5 million deaths attributable to physical inactivity annually[37]. Such integrated approaches can reduce climate impacts, support active transport and create more liveable, equitable urban environments[38].

Beyond these direct co-benefits, many climate adaptation strategies have the potential to strengthen public health. Building climate-resilient healthcare systems is critical to managing rising climate risks and to improve preparedness for other threats, such as infectious disease outbreaks and extreme weather events. Public health interventions that promote physical activity[11] may further enhance resilience by improving population health and reducing pressure on overstretched health systems. While evidence clearly links physical activity to better cardiovascular, respiratory and mental health, its role in improving tolerance to climate-related stressors, such as heatwaves or air pollution, is less well established. Nonetheless, the chain of reasoning is compelling: healthier individuals may be more physically and psychologically resilient, and reduced strain on health systems could enhance societal adaptive capacity. To maximize these benefits, physical activity promotion must be aligned with policies[23] that simultaneously cut emissions and adapt systems across multiple sectors to reduce climate change.

However, the burden of climate change is experienced unevenly. Those contributing the least to GHG emissions, that is, LMICs, often face the most severe impacts[39]. The top 10% of global emitters (for example, USA, India, China and Europe) are responsible for nearly half of global emissions, while the lowest-emitting 50% of countries account for just 10% of emissions, yet bear a disproportionate share of climate-related harms[39]. This inequity has prompted urgent calls from LMICs for HICs to share the financial burden of mitigation and adaptation more equitably, and to reconsider growth models that prioritize economic expansion and planetary health. Despite progress in some HICs towards renewable energy transitions, LMICs often remain dependent on oil and gas, becoming the new market for the fossil fuel industries and reinforcing patterns of car dependency.

The inclusion of 'climate-resilient development' in the Intergovernmental Panel on Climate Change Sixth Assessment Report marks a critical evolution in global climate discourse. Climate-resilient development acknowledges the right of developing nations to pursue economic growth and improve living standards, while avoiding the environmental degradation historically associated with economic growth. Physical activity can support climate-resilient development by advancing sustainable urban design, reducing reliance on carbon-intensive transport and improving health equity. To ensure equitable outcomes, LMIC communities must be central to co-creating solutions and HICs must commit to investments tailored to the needs of vulnerable populations.

Several initiatives illustrate this principle in action. In Nigeria, the Lagos Urban Transport Project integrated pedestrian infrastructure in low-income areas through stakeholder and community consultations, although rapid urbanization continues to challenge progress, highlighting the need for continued community engagement[40]. In India, the grassroots Raahgiri Days movement reclaimed urban streets for walking, cycling and social connection, showing how locally driven actions can advance both health and environmental goals[41]. Across Pacific island countries, the Nature-Based Solution Project, led by the Pacific Community, embeds traditional knowledge in participatory design for climate-adaptive, movement-friendly urban spaces[42]. HIC-supported investments have also contributed to the development of equitable models. For instance, the Wellcome Trust's Climate and Health Initiative funds LMIC-led co-designed research including projects promoting active environments. Similarly, the Urban-LEDS I & II project, funded by the European Commission and implemented by the global network Local Governments for Sustainability and UN-Habitat, has supported cities in Rwanda, Bangladesh and Jakarta to develop inclusive, low-emission urban strategies prioritizing walkability.

Our work identifies key barriers to sustained progress on both climate change and physical inactivity, chief among them, the underutilized potential of community participation. Enabling communities to actively shape priorities and co-design solutions is critical for ensuring equitable contextually relevant interventions and minimizing unintended consequences[12]. Case studies demonstrate how communities are already developing locally tailored responses to these interconnected challenges. Indigenous ancestral knowledge, for example, reflects deep connections between people and place. In Aotearoa New Zealand, Māori perspectives on person–environment connections inform community-driven approaches to health, well-being and sustainability. Among Turkana people in Kenya, who face disproportionate climate impacts, customary practices, cultural identity and social cohesion are integral to emerging climate and health strategies[43].

Despite notable examples of community engagement in climate health initiatives, most climate policies continue to rely on top-down approaches that limit opportunities for informed, participatory and shared decision-making. The absence of community-driven processes, coupled with competing interests, such as those of industry versus climate and health objectives, often results in solutions that cater to more affluent populations while overlooking cultural, social and local priorities. Urban green spaces, for instance, are frequently designed for affluent neighbourhoods, with limited consideration of broader community needs, such as space for community gardening, accessible playgrounds or inclusive sports facilities. In contrast, community-driven approaches leverage the diversity of local knowledge and lived experience to design equitable, relevant and sustainable solutions. Social networks such as those found in Pacific churches can serve as a catalyst for behaviour change and community cohesion. Building trust and meaningful partnerships, rather than limiting engagement to consultations, is essential to achieving equitable, effective policies. We argue that physical activity[2] and climate change agendas should be aligned through shared goals, tools and metrics that reflect the priorities of those most affected.

As the consequences of climate change intensify, reclaiming the outdoors in ways that are both safe and sustainable has become critical. Governments can support this by investing in health-promoting, climate-resilient outdoor spaces, alongside policies and regulations that prioritize protection of vulnerable communities. Adapting outdoor environments requires collaboration across transport, urban planning, sport, education, health, business and finance sectors, working in partnership with community representatives, Indigenous leaders and public organizations.

While integrated physical activity and climate change strategies offer substantial potential, they also produce unintended consequences if not carefully designed. For example, compact city planning can inadvertently drive gentrification, displacing lower-income residents to areas with reduced access to healthy environments. Policies that fail to provide sustainable active transport and accessible public transit infrastructure further reinforce car dependency, disproportionately affecting those without cars, and forcing them to engage in physical activity in risky environments characterized by crime, traffic hazards and poor infrastructure[4].

Urban policies informed by climate and physical activity considerations can anticipate and mitigate these risks. For instance, while electric cars are often promoted as scalable solutions for reducing GHG emissions, they offer limited health benefits compared with active transport. Moreover, their emissions reductions varies substantially depending on assumptions made during modelling and comparative studies. An over-reliance on electric cars risks perpetuating traffic congestion, physical inactivity, traffic-related injuries and car dependency, deepening social and spatial inequities. In contrast, investing in active transport infrastructure offers a more balanced, equitable alternatives, promoting health, reducing emissions, and improving long-term population and planetary health[44].

Achieving equitable, climate-resilient development also requires anticipating future demographic and environmental shifts. Africa is projected to play a central role in shaping global environmental trajectories in the second half of the twenty-first century[45]. Countries such as Nigeria, the Democratic Republic of the Congo and Ethiopia are expected to experience a dramatic population growth, accompanied by rising energy demands and rapid urban expansion. This demographic shift presents both challenges and opportunities. On the one hand, unchecked emissions growth could substantially impact global climate targets; on the other hand, there is a critical window to support sustainable development pathways that prioritize clean energy, resilient infrastructure and inclusive health systems. Recognizing Africa's influence is essential for crafting equitable and forward-looking climate strategies that align with the principles of climate-resilient development[45].

This paper highlights the bidirectional relationship between physical activity and climate change. We do not propose physical activity promotion as the 'silver bullet' for the climate crisis, nor will climate action alone resolve the inactivity crisis. However, addressing both challenges together offers the potential for synergistic cross-sectoral benefits for health, the environment and society[46]. Raising awareness of these interconnections and accelerating action that delivers co-benefits for people and the planet must become a priority for public health and climate agendas.

Scalable and evidence-based solutions[34] already exist that can promote physical activity, reduce emissions, improve energy efficiency, support climate adaptation and advance health equity. The broader health community, including clinicians, public health professionals, physical activity scholars and advocates, is well positioned to contribute to global efforts to limit environmental degradation while promoting healthier, more resilient and more equitable societies.

We call on governments, the World Health Organization, the United Nations and the Intergovernmental Panel on Climate Change to enable these strategies. This requires an integrated, multisectoral and collaborative approach, one that centres on community voices and ensures that policy change and funding decisions advance climate goals while delivering healthier, more just and more resilient communities.

Methods

Overview

This paper integrates evidence from multiple sources to explore the intersection of physical activity and climate change. To inform conceptual development, a multidisciplinary group model building (GMB) process was undertaken, involving experts in physical activity, public health, climate change and systems science. Through structured activities, the team applied a systems lens to the eight best investments for physical activity promotion, exploring multilevel interactions and feedback mechanisms (Extended Data Figs. 1–8). The resulting PACC conceptual model was validated through iterative feedback from a senior expert committee. In addition, a double scoping review was conducted to examine built environment exposures, active transport outcomes and associated GHG emissions, providing a foundation for identifying co-benefits and unintended consequences of integrated interventions. Lastly, a case study analysis using cycling data from Denver, Colorado, USA, was conducted to illustrate how extreme heat events influence physical activity patterns, with detailed methods provided below.

PACC conceptual model

Process overview. We used a structured, iterative process to develop an overarching conceptual model illustrating the complex systems linking physical activity and climate change. The model was informed by principles of systems thinking and GMB, and draws on qualitative causal mapping tools to explore interconnections, feedback mechanisms and potential unintended consequences associated with aligning these two agendas.

Participants. The GMB participants comprised a core group who developed the model ($n = 7$) and a broader expert group of distinguished researchers who provided feedback to refine the model ($n = 8$). The groups were internationally diverse with participant backgrounds (for example, Australia, Brazil, Columbia, New Zealand, Mexico, Norway, USA). Forty per cent of participants were female. Expertise spanned from physical activity, built environment, climate change, system dynamics modelling, urban planning and design, public health, health policy, behavioural science, urban health, health equity, climate resilience, to environmental epidemiology. All participants were academic collaborators who contributed as part of their professional roles. We consulted with the ethics office and we were advised that no approval was required as no primary data were collected from human participants external to the research team, and the process did not involve collection of identifiable personal information, behavioural interventions or outcomes research. The GMB workshop and subsequent sessions were part of a co-authorship and co-creation process focused on system conceptualization. All contributors participated voluntarily and with full awareness of the project's aims, and all are acknowledged as co-authors on the resulting publication.

Selection of participants. This project was explicitly focused on convening experts and scholars in the fields of physical activity and climate change research. Participants were purposively selected based on their recognized expertise and leadership in the fields of physical activity, public health, climate change and systems science, particularly system dynamics modelling. Recruitment was guided by the principle of assembling a diverse group of thought leaders capable of contributing deep disciplinary knowledge while engaging in transdisciplinary dialogue. Individuals were identified through professional networks, existing collaborations and their scholarly contributions to their respective fields. This purposive sampling ensured that the workshop included participants with the capacity to critically engage with complex systems thinking and contribute to the co-construction of a shared model integrating the physical activity and climate change agendas. The research team was composed of a core group ($n = 7$) and a broader expert group of researchers ($n = 10$).

GMB. We selected GMB over other participatory mapping methods, because it is grounded in systems science and the system dynamics tradition, to help us uncover the nuanced interrelationships, barriers, enablers and potential unintended consequences of integrating the physical activity and climate change agendas[47]. System dynamics mapping and modelling provide a visual language to represent the complex, adaptive challenge requiring an approach capable of capturing feedback loops, time delays and nonlinear dynamics. GMB, as part of the broader system dynamics modelling (SDM) approach, provided a structured yet flexible way to engage the researchers mapping these interconnections by both integrating published literature and well researched links, as well as links that are understudied, hard to document, or informed by lived experience and practice knowledge. This integration of qualitative and experiential knowledge with published empirical and theoretical knowledge creates a platform that supports identification of potential leverage points to co-create pathways for synergistic action. Its emphasis on feedback mechanisms aligns well with our goal of understanding the systemic interactions that shape both agendas. Importantly, the use of GMB here is intended to inform the conceptualization of the structure that could be refined, improved or validated through multiple formal methods of quantitative and qualitative modelling in the future.

From 31 January to 2 February 2023, a multi-day exploratory GMB workshop was held in St. Louis. This workshop brought together experts specializing in the fields of physical activity, public health, climate change and system dynamics modelling (E.B., R.R., E.H., D.D., P.C.H. and T.B.).

The primary objective of these workshops was to expose the team to a system mapping approach, grounded in systems thinking to comprehend how the eight investments that work for physical activity might be used to address climate change. The aim was to grasp the nuances, barriers, facilitators, potential pitfalls and unintended consequences—all essential aspects to be considered with the goal to merge the two agendas[47]. Recognizing the intricacies of this challenge, complexities were explored within a systemic perspective. The methodology was based on the principles and tools of SDM and GMB predominantly using feedback as the lens to analyse the interconnections between physical activity and climate change.

The SDM approach directly examines the interconnections between concrete elements such as urban infrastructure, school facilities and motorized vehicles, and abstract factors such as perceptions, social influences and information. Analogous to a GMB effort, structured exercises were conducted to pinpoint variables and subsequently produce increasingly detailed qualitative diagrams. These diagrams shed light on the generic representations of a system, focusing on its interconnections and feedback mechanisms[48].

Valuable evidence and expertise concerning the eight investments that work for physical activity were drawn upon to initially discuss the complexity of the problem, barriers, facilitators and other relevant aspects on the different investments[47].

Subsequently, the facilitator reviewed basic GMB principles and presented a series of seed questions aimed at guiding the focus of variable elicitation, with consideration given to historical contexts and evolution on initiatives over time and possible social influences.

A shared list of relevant factors was generated by the participants considering the previous step. Following this, participants engaged in discussions to nominate causal links or interconnections among the selected factors, articulating the mechanisms that constitute each investment.

The visual depiction of the causal structure enabled participants to elucidate the pathways through which the factors comprising each of the eight investments exhibit synergistic or opposing relationships to climate change. This facilitated discussion took place during the workshop and was simultaneously transcribed into an analogical diagram, commonly referred to as a 'seed structure'. This representation was subsequently digitized using the Kumu platform (https://kumu.io).

Confidence-building process. After the preliminary workshop sessions, the facilitator (E.B.) synthesized the data from the causal loop diagrams. In addition to these diagrams, the facilitator gathered discussion notes and session artefacts to provide a foundation for further analysis and interpretation. Once the material was systematically organized, discussions were conducted over 6 months with different group members, facilitated by E.B. During these discussions, participants engaged in an iterative review process. This involved re-evaluating the content through expert opinions and identifying potential gaps or inaccuracies in the information conveyed in the diagram.

A key component of this review was determining whether the identified pathways were logical and sound. This extensive review and iterative feedback mechanism is termed in traditional GMB and SDM exercises the 'confidence building'. The confidence-building process in SDM and GMB enhances the model's credibility and trustworthiness. It is an approach where confidence in a model's usefulness is built incrementally by applying various validation tests. Fundamentally, validation is integral to every stage of the modelling process, extending even to the phases of model implementation and utilization.

However, it is worth noting that the approach we undertook deviates from the traditional GMB confidence building that may engage with a broader range of stakeholders who experience and work in intervening around the issues of study. A cornerstone of our validation argument is the belief that experts must spearhead the foundational theories, especially those surrounding the interconnections of physical activity and climate change. It would be impractical and unreasonable to delegate this intricate task to the broader community and in fact at this formative stage and broad scale may be a misuse of community voice and effort.

Concluding the confidence-building process, two critical sessions were held on the 20 and 21 July 2023. These sessions were composed by the distinguished international experts in the field. During these sessions, feedback, comments and suggestions were collected, which further refined the structures that articulate the underlying relationships between physical activity and climate change.

Adaptations made and refining the PACC framework. The GMB process informing the development of the PACC model was both structured and adaptive. While grounded in established system dynamics protocols, the process was modified to suit the interdisciplinary and exploratory nature of the research aim, namely, to understand how physical activity investment strategies intersect with climate change mitigation, adaptation and impact pathways.

Adaptations to standard GMB scripts. Initial discussions began with the facilitator presenting a rough conceptual framework to seed dialogue among core team members. This early sketch prompted reflection on key climate dimensions, such as extreme weather events (for example, heat and drought), pollution and climate migration, elements drawn from the Intergovernmental Panel on Climate Change Sixth Assessment Report[38] and The Lancet Countdown framework[49]. Importantly, the facilitator adjusted the variable elicitation script to broaden focus beyond traditional health determinants of physical activity, encouraging participants to explore upstream climate factors and their potential feedback with the physical activity system. Also, the facilitator applied a variation of the Graphs over Time script to engage us on framing the problem and variable elicitation as a way to frame the problem to be modelled[50].

Analysis of causal loop diagrams and iterative refinement. Following the initial workshop, the facilitator synthesized participant input into an analogue causal structure, which was digitized in Kumu and shared with participants for validation. Over a 6-month period, the research team engaged in iterative consultations to refine this structure. Through these discussions, it became clear that conventional polarity notations (positive/negative links) in causal loop diagrams risked oversimplification and reader confusion. The group reached consensus to adopt a more narrative-based visualization, removing polarity symbols while maintaining the depiction of reinforcing and balancing loops. This adaptation allowed greater flexibility in capturing complex interactions without overstating causality. An important insight that emerged was the importance of distinguishing between direct and indirect contributions of the eight investment areas to climate change mitigation. For example, active transport and urban design offer clear mitigation benefits, while other strategies (for example, workplace programmes or healthcare advice) support physical activity but do not inherently reduce emissions unless embedded within wider systemic interventions. This differentiation informed the reorganization of the model to highlight synergistic, supportive and catalytic roles of each investment (as presented in the lower part of Fig. 1).

Final conceptualization of the PACC model. Rather than aiming for a fully quantified systems map, the team reframed the output as a conceptual feedback structure, illustrating the dynamic and interconnected roles of physical activity strategies in the climate system. The agreed-upon convention was to label the loops generically as 'feedback loops' to maintain explanatory clarity. This allowed the final model to serve as both a synthesis of shared understanding and a heuristic for future research and action. Finally, in October 2023, during an internal in-person peer review meeting (5 days) that took place in Auckland, New Zealand, the model was confirmed by the wider group of academic experts, $n = 9$ (the co-authors from refs. 22,27).

Kumu software. Kumu (https://kumu.io) is an online visualization and systems mapping platform designed to organize complex information and reveal relationships among variables in a clear, interactive format. It is particularly well suited for systems thinking, stakeholder mapping and causal loop diagramming, making it a valuable tool for participatory modelling processes such as GMB. For more information, visit the platform's website https://docs.kumu.io/about-kumu/what-is-kumu. Kumu enables users to:

- Input elements (for example, variables, actors, concepts) and define their attributes.
- Create and visualize connections between elements to represent causal or relational links.
- Categorize and group elements using tags or fields for analytical clarity.
- Annotate links to describe their nature, strength or direction.
- Share interactive, web-based maps that can be navigated, filtered and layered for different audiences or analytical purposes.

Kumu addresses the challenge of making complex systems understandable and navigable. It offers a flexible and visually engaging interface, and supports the iterative co-creation and validation of system maps. It simplifies the representation of feedback loops, interdependencies and nonlinear relationships, key aspects of system dynamics modelling, without requiring advanced coding or technical expertise. Key characteristics include:

- Web-based interface: accessible from any device with an internet connection; no local installation required.
- Interactive visualization: maps are dynamic and navigable, facilitating stakeholder engagement and collaborative analysis.
- Customizable structure: elements, links and views can be tailored to different conceptual frameworks or user needs.
- Collaboration features: supports real-time editing and commenting among team members.
- Integration ready: maps can be embedded in websites or linked to external data sources for expanded functionality.

In the present study, Kumu was used to digitize and refine the maps generated during the initial workshop. It served as both an analytical tool and a communication platform, allowing the research team to iteratively review, validate and refine the eight investments maps that reciprocally informed the PACC model.

Scoping reviews on the co-benefits of built environment investments for improving active transportation and reducing emissions

Two scoping reviews were conducted in parallel to investigate the opportunity that exists to simultaneously improve health while lowering GHG emissions by instituting transport-related policies and interventions that encourage active transportation via the built environment. Three distinct groupings of built environment interventions were selected from prior review of the literature to focus the scope of the reviews around and to include land-use mix, population and/or residential density, and streetscape components (for example, crosswalk/sidewalk improvements, traffic calming features, lighting and so on). The first aim was to search for and select studies that included data regarding the relationship between characteristics within the three built environment intervention groupings and active transportation outcomes. Correspondingly, the same was done for those built environment interventions and estimations of GHG emissions or reduction estimations.

The first component of the review comprised searching Google Scholar using a variety of keywords relevant to active transport (utilitarian, physical activity, active transport, active mobility) and built environment (built environment, interventions, profiles, urban, land-use mix, population density, residential density, streetscape). Focusing first on systematic reviews, each article was screened and included if they reported on the relationship between built environment characteristics and active transport outcomes. Data were extracted and added to a comprehensive table with relevant details such as the built environment intervention, active transport outcome measured, details on data sources, analysis method, estimates of association and any quality assessment information. References of included papers were also screened for relevant studies. A similar approach was taken to locate and extract data quantifying the impact of built environment interventions of interest on GHG measures (that is, vehicle miles travelled, travel, speed and emissions, change in motor vehicle speed and volume, and so on). Additional keywords were added to the search terms related to GHGs, emissions reductions and quantification. As no systematic reviews exist linking the built environment characteristics under investigation and GHG-related measures, articles returned on Google Scholar were screened and incorporated if a quantification of the association between the two variables was included.

The impact of 100-degree days on bicycling in Denver, Colorado, summer 2022

Overview. Extreme heat events are becoming more common throughout the USA and worldwide[7]. These heat events are exacerbated by climate change and by the micro heat island effect. In parallel, municipalities are encouraging active transportation, specifically bicycling, for its health and environmental benefits. Unfortunately, when temperatures become extremely hot, bicycling may become less comfortable and even unsafe owing to the health risks of exertion at extremely high temperatures. Like many parts of the world, Denver, Colorado, has been experiencing more extreme heat events over the past decade. The impact of extreme heat on observed bicycling has been explored in a few places and warrants investigation in Denver as well. In this quasi-experimental study, we estimate the effect of extreme heat on observed bicycling in the Denver area.

Data sources. The study was set in Denver, Colorado, over June, July and August 2022 (92 consecutive days). We downloaded daily data on maximum air temperature from the National Oceanic And Atmospheric Administration Climate Data Online Search Tool (https://www.ncdc.noaa.gov/cdo-web/search; accessed 21 April 2023). Of the 37 stations present in the downloaded dataset from the City and County of Denver (henceforth, Denver), 3 had no missing data on maximum temperature during this time period. We used measurements from the Denver Water Department (station ID USC00052223) because of its central location in Denver. We gathered daily data (called 'daily summaries' in the online tool) at this location on maximum temperature and amount of precipitation.

To measure bicycling, we used data from Strava Metro. Strava is an app used by about 5–15% of bicyclists to track their activities. Strava makes their data available via Strava Metro to qualifying organizations in an anonymized format. We obtained the number of rides observed on every segment of street and trail in the study area (n = 251,068 segments) on every day in June, July and August 2022. We calculated bicycle distance ridden on these segments by multiplying the number of rides on the segment by the segment's length. We then summed that bicycle distance over all segments by month for a monthly total.

Analysis. We classified days with extreme heat as those with a measured air temperature of at least 100 °F (12 of the 92 days). We refer to the 80 days with an air temperature of 99 °F or below as control days and the other 12 days as treatment days. We then estimated estimate the effect of extreme heat on daily bicycle distance ridden. Broadly, our approach was to estimate counterfactual bicycle distance ridden during the treatment days had the temperature not been 100 °F or more and compare it with the observed value. To estimate counterfactual bicycle distance during the treatment days, we first fit a linear regression model estimating daily bicycle distance ridden in the control days. The predictor variables in the model were the month (treated as a categorical variable, each level modelled against a referent), the day of week (categorical variable, each level modelled against a referent) and the amount of precipitation (continuous variable). We then used the coefficients from that model to estimate counterfactual bicycle distance ridden on each treatment day using those day's values of month, day of week and precipitation. We fit the model on the control day only so that when the model is applied to the treatment data, we are effectively asking the model to answer the question: if the treatment day had the same value of month, day of week and amount of precipitation as a comparable day among the control days, how much bicycle distance would have been ridden?

We estimated difference ($BD_{observed} - BD_{estimatedcounterfactual}$) and ratio ($BD_{observed}/BD_{estimatedcounterfactual}$) effects.

The effects we estimate are 'effects of treatment on the treated' in that we estimate the effect of extreme temperature for the treatment days only. To estimate uncertainty in the effect estimates, we took a bootstrapping approach. We re-sampled residuals from the vector of the model's residuals (observed value − predicted value), sampling from a normal distribution (mean = mean of the residuals, standard deviation = standard deviation of the residuals) and added the re-sampled residual to that day's predicted value to obtain a re-sampled predicted value for each day. We used that re-sampled value in all downstream calculations to estimate re-sampled effect estimates. We conducted 1,000 replications of this procedure and took the 2.5th and 97.5th percentiles of corresponding measures as their 95% CI.

Ethics statement

All participants were academic collaborators contributing in their professional capacity as part of a co-authorship and co-creation process focused on systems conceptualization. Following consultation with the institutional ethics office (University of Sydney, 2023), we were advised that ethics approval was not required, as no primary data were collected from individuals external to the research team, and the process did not involve identifiable personal information, behavioural interventions or outcomes research. As such, the activity did not fall within the scope of research requiring human ethics approval under relevant national and institutional guidelines. All contributors participated voluntarily, with full awareness of the project's objectives, and are acknowledged as co-authors on this publication.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The Kumu PACC projects are made available under the Open Database license: http://opendatacommons.org/licenses/odbl/1.0/. Any rights in individual contents of the database are licensed under the Database Contents license: http://opendatacommons.org/licenses/dbcl/1.0/ The iterative work is available through the following links. (1) Initial conceptualization (2023): https://kumu.io/eaballar/physical-activity-climate-change-master#conceptual-framework-ccpa/landing-page. (2) Working maps informed by core team (2023): https://kumu.io/eaballar/physical-activity-climate-change-working-project#0-landing-page. (3) Working maps for internal review by wider team (2023): https://kumu.io/analuiza/physical-activity-climate-change-folk-internal-review. (4) Final maps for internal review by wider team (2023): https://kumu.io/analuiza/physical-activity-climate-change-final-internal-review#overall-climate-impacts-dynamic-framework-final. (5) Final maps (2024): https://kumu.io/analuiza/physical-activity-climate-change-final-internal-review#overall-climate-impacts-dynamic-framework-final. For the case study in Denver, Colorado, over June, July and August 2022 (92 consecutive days), we downloaded daily data on maximum air temperature from the National Oceanic And Atmospheric Administration Climate Data Online Search Tool (https://www.ncdc.noaa.gov/cdo-web/search; accessed 21 April 2023). The scoping review data are available in Supplementary Dataset 1.

Code availability

No custom computer code or algorithm was developed for this study. All analyses were conducted using standard linear regression and bootstrap methods implemented in commonly available statistical software. The code used to implement these methods is available upon request from the corresponding author. The code will be shared within 10 business days of the request.

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Author contributions

All authors provided input and expertise to the relevant sections. E.H. conceptualized the paper and led all aspects of the work including supervision, conceptual model and figure interpretation, critical appraisal of the literature, visualization, validation, administration, funding acquisition, writing—original draft, reviewing and editing. R.R. contributed to the conceptualization, interpretation, critical assessment of the literature, conceptual model and figure, all sections, led the vulnerable populations and policy sections, provided guidance and support, and writing—original draft, reviewing and editing. M.R. contributed to direction of manuscript, interpretation and writing, reviewing and editing. D.D. contributed to the conceptualization, interpretation, critical assessment of the literature, conceptual model and figure, all sections, led the reclaiming the outdoors section, administration, guidance and support and writing—original draft, reviewing and editing. I.A. contributed to the vulnerable populations and introduction sections and writing, reviewing and editing. A.L.F.L. contributed to the conceptualization, conceptual model and figure, software, visualization, unintended consequences and model sections, led figure design, writing—original draft, reviewing and editing. E.B. contributed to the conceptualization, unintended consequences, software, visualization, led the conceptual model and figure and model section, writing—original draft, reviewing and editing. T.B. contributed to the conceptualization, model and figure, led the scoping reviews, data analysis, figures, interpretation, provided critical assessment of literature, writing—original draft, reviewing and editing, J.F.S. contributed to the interpretation and writing, reviewing and editing A.B. contributed to the interpretation and writing, reviewing and editing. A.R.V. contributed to the interpretation and writing, reviewing and editing. D.S. contributed to the interpretation and writing, reviewing and editing. R.H. contributed to the Indigenous case study section, reviewing and editing. U.E. contributed to the interpretation and writing, reviewing and editing. M.P. contributed to the interpretation and writing, reviewing and editing. I.-M.L. contributed to the interpretation and writing, reviewing and editing. H.W.K. contributed to the conceptualization—original draft. P.C.H. contributed to the conceptualization, conceptual model and figure, interpretation, critical assessment of the literature, led the introduction section and contributed to all sections, provided overall guidance and support, administration, communications, and writing—original draft, reviewing and editing.

Competing interests

The authors declare no competing interests.

Additional information

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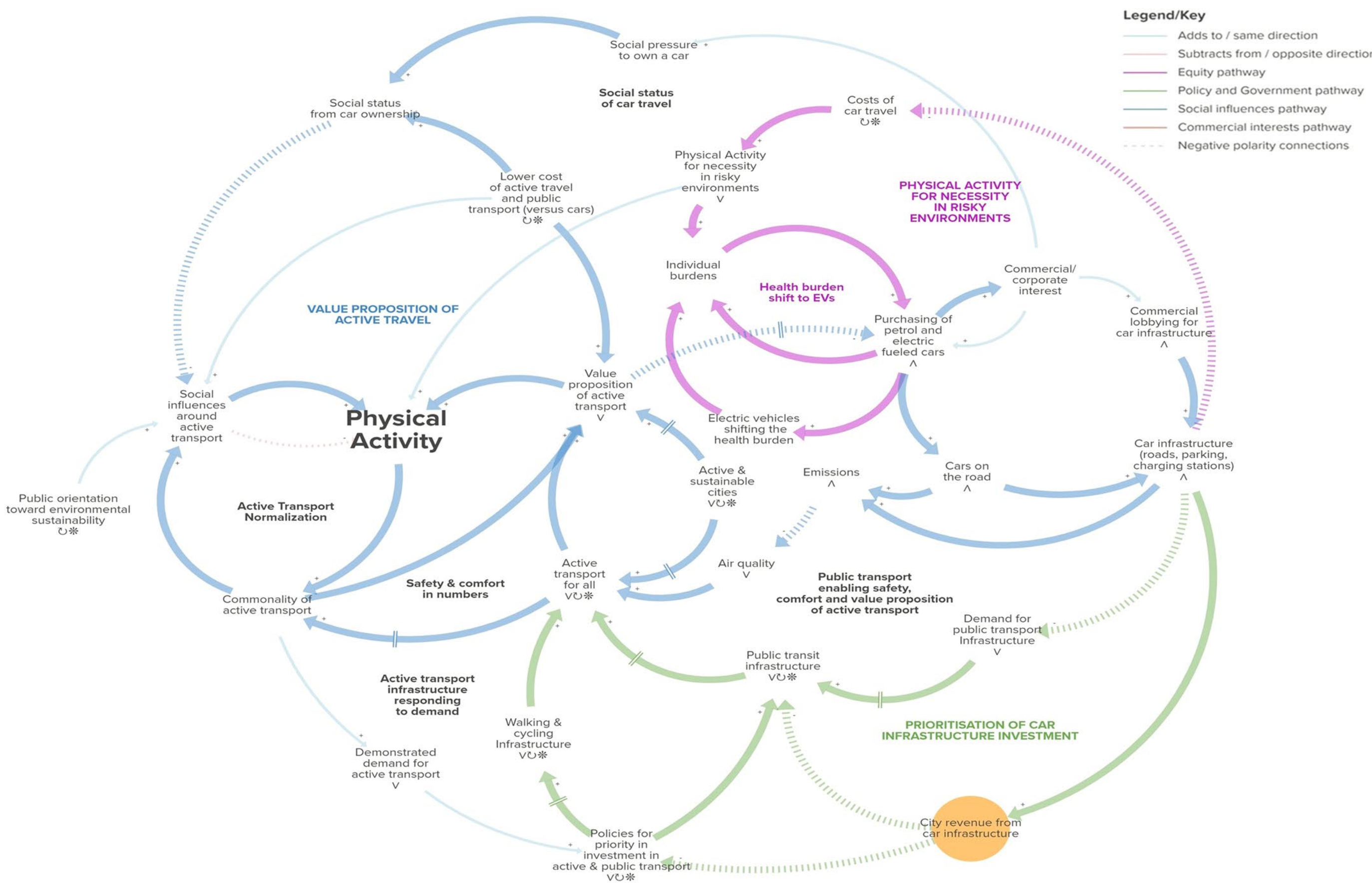
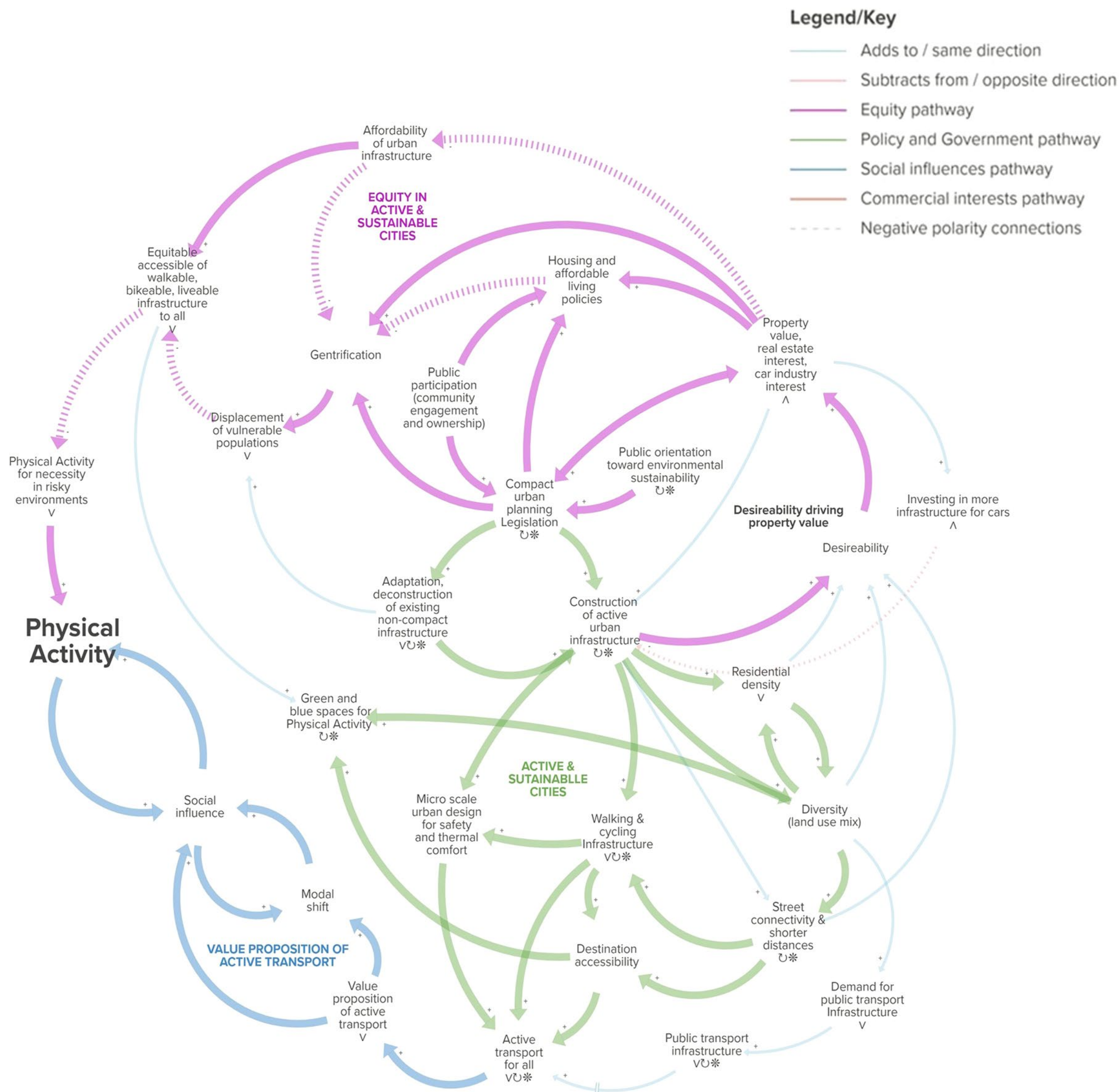


Extended Data Fig. 1 | Active transport conceptual map. Depicts the system-wide impacts of promoting walking, cycling, and public transit over car use. Highlights emission reductions, improved air quality, and increased population-level physical activity as climate mitigation and public health outcomes. Dominant pathways: Policy and Government, Equity, Social Influences.



Extended Data Fig. 2 | Active urban design conceptual map. Explores the role of planning policies and built environment interventions such as mixed land use, green spaces, and pedestrian-friendly streets, in creating movement-supportive environments that reduce car dependency and promote climate-resilient communities. Dominant pathways: Policy and Government, Equity, Social Influences.

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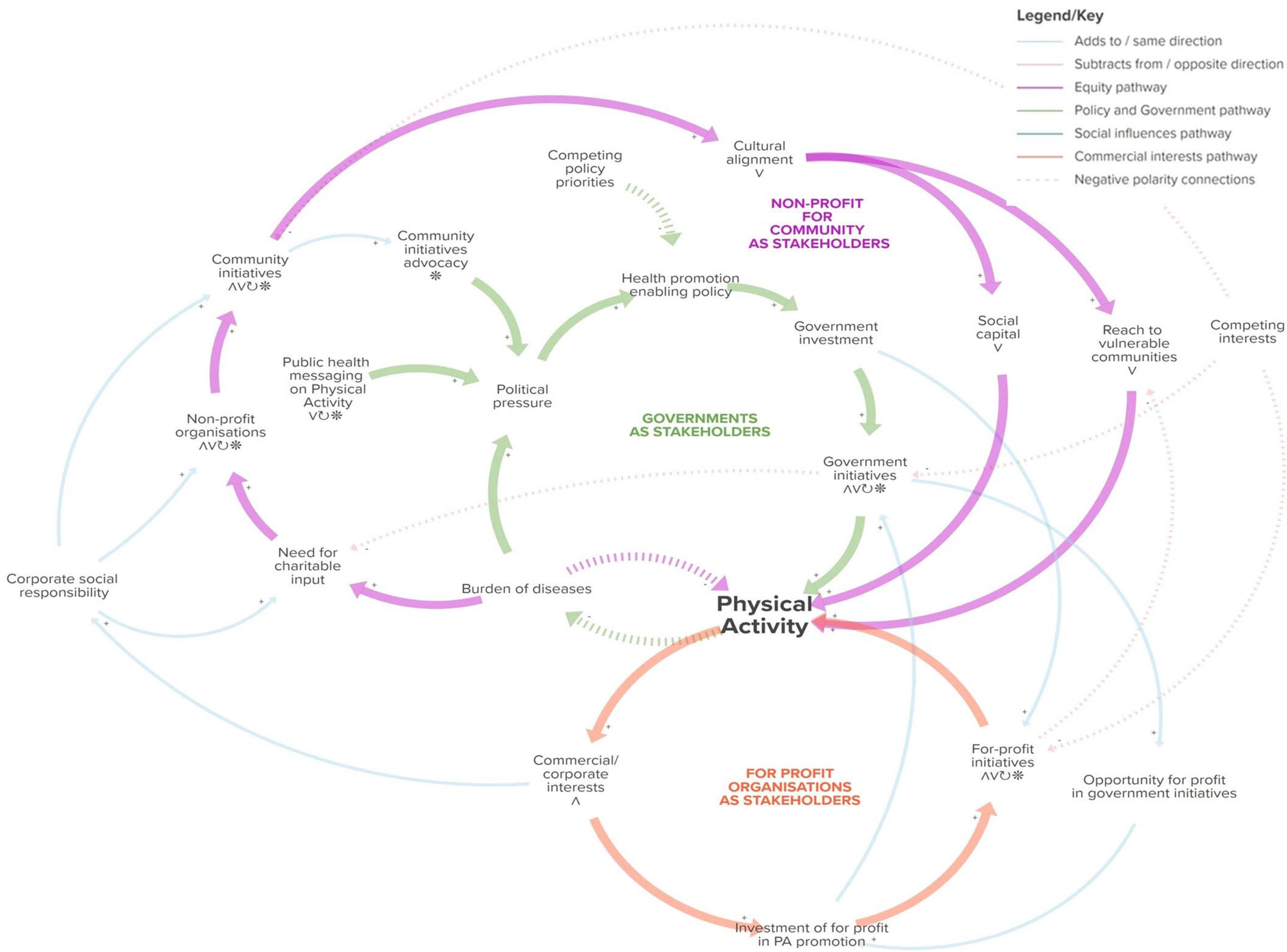

Extended Data Fig. 3 | Community-wide programs conceptual map. Shows the system-level influence of locally designed initiatives that build community ownership, support environmental stewardship, and ensure culturally responsive, climate-conscious solutions. Dominant pathways: Policy and Government, Equity, Commercial Interests.

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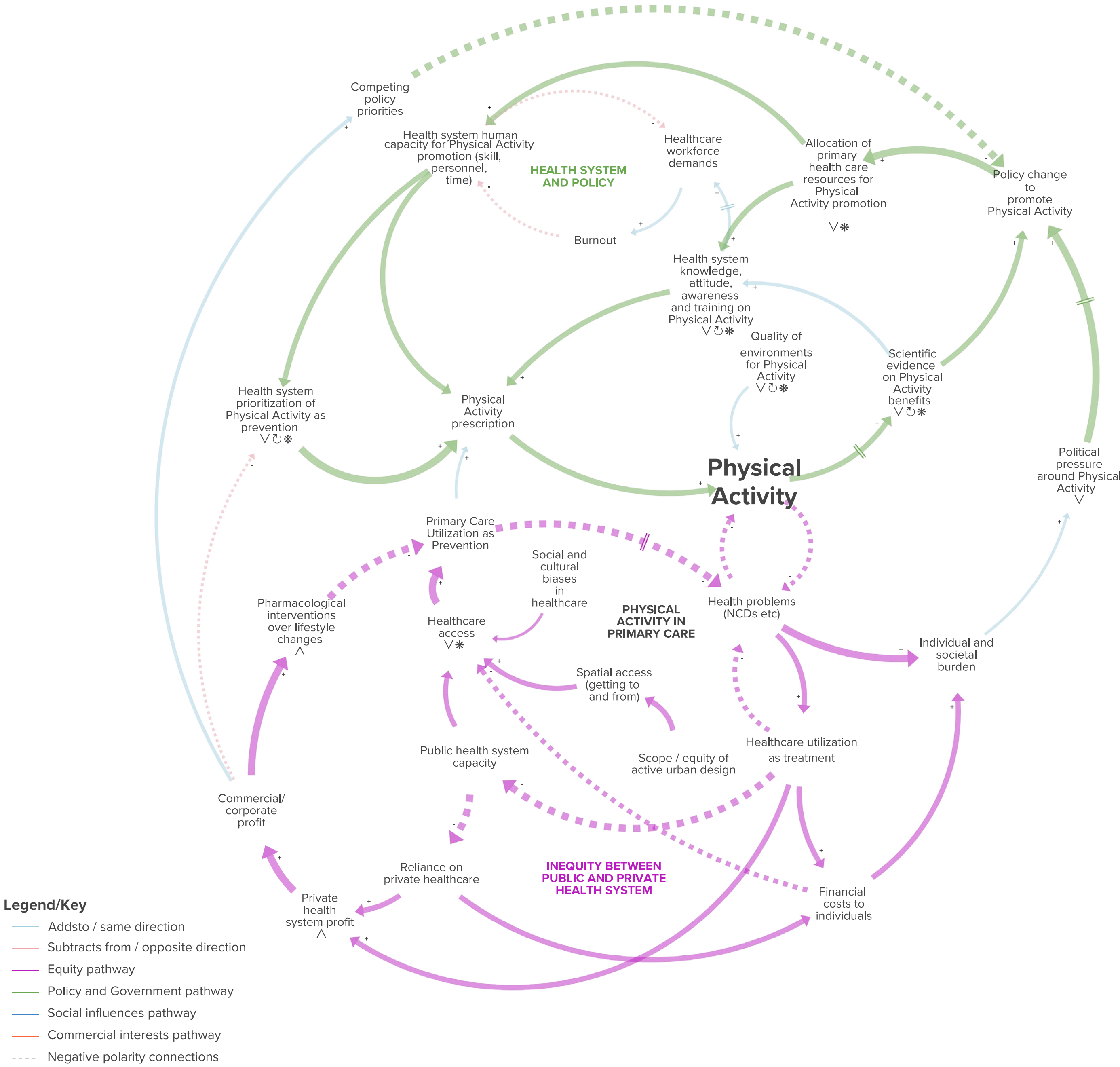

Extended Data Fig. 4 | Healthcare conceptual map. Shows how integration of physical activity into primary healthcare supports prevention and management of non-communicable diseases, with potential climate co-benefits through reduced healthcare system strain and emissions. Dominant pathways: Policy and Government, Equity, Commercial Interests.

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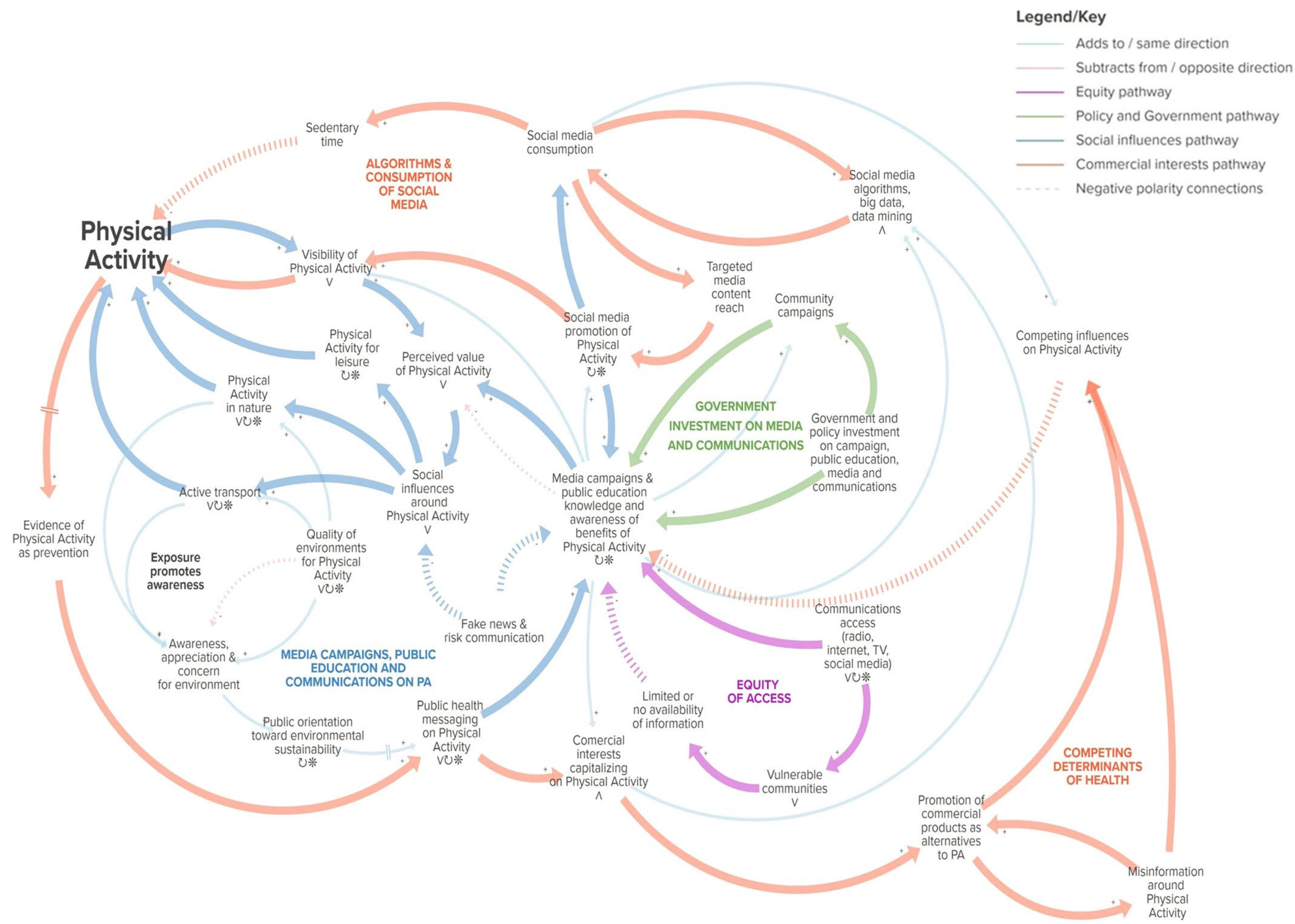
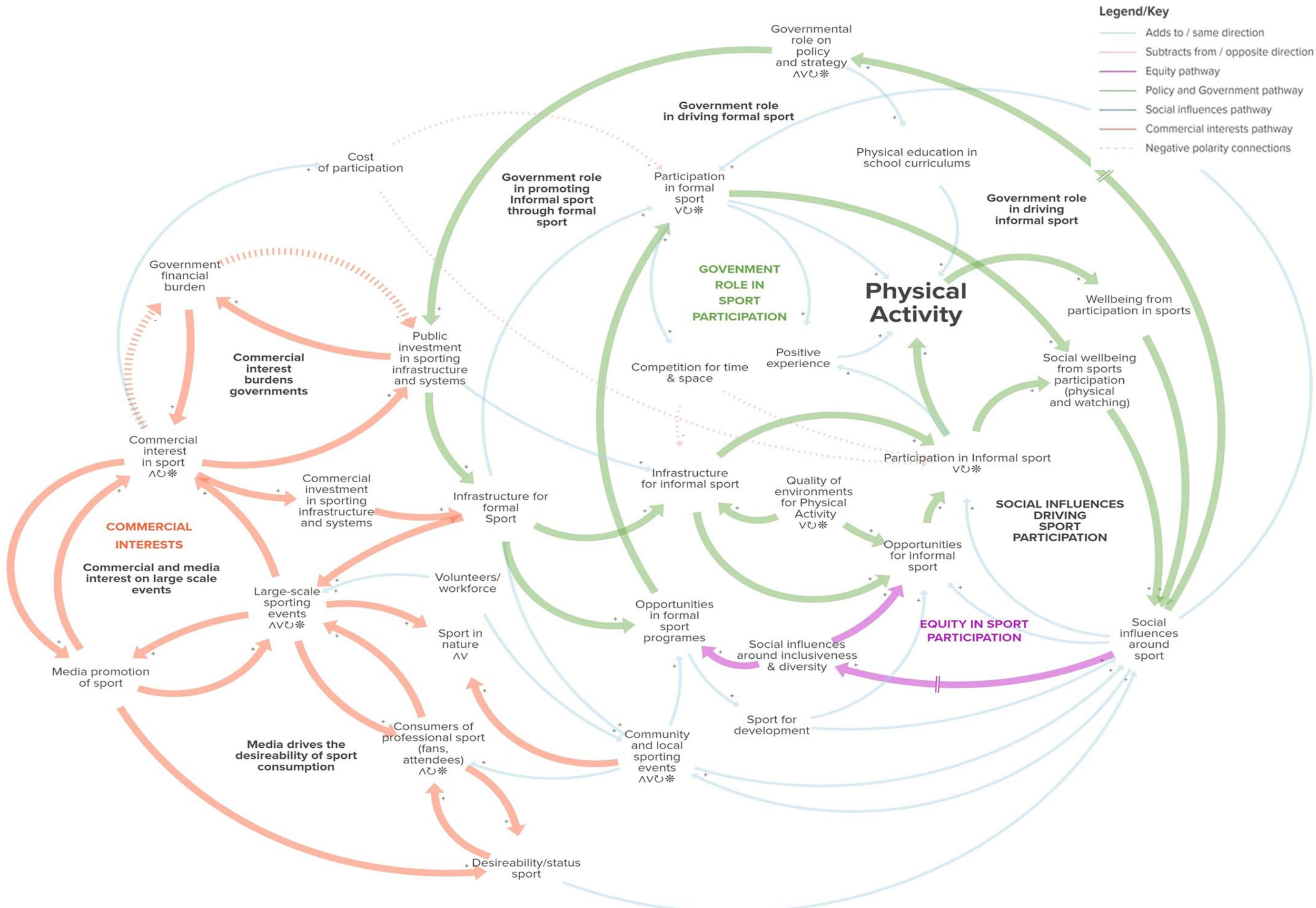


Extended Data Fig. 5 | Public education & mass media conceptual map. Demonstrates how coordinated campaigns raise awareness about the dual benefits of movement for health and climate, supporting behavioural shifts and public support for policy changes. Dominant pathways: Policy and Government, Equity, Commercial Interests and Social Influences.



Extended Data Fig. 6 | Sport and recreation for all conceptual map. Highlights the government's role in sport participation, equitable access to low-emission recreation settings and implications of commercial and media interests in large-scale events. Dominant pathways: Policy and Government, Equity and Commercial Interests.

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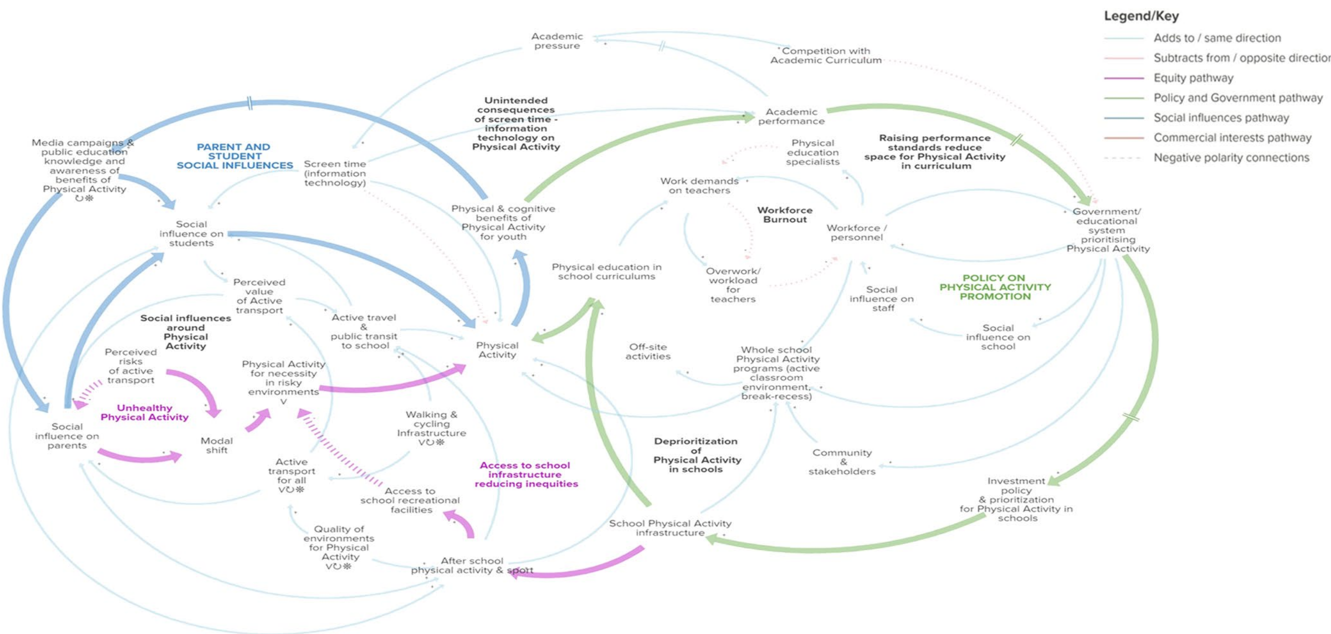

Extended Data Fig. 7 | Whole-of-school programmes conceptual map. This map illustrates the importance of physical activity promotion through school-based interventions and curriculum, safe infrastructure for walking and cycling to school, and the importance of social influences for behavioural change. Climate co-benefits include reduced emissions from active commuting and improved community resilience through healthier children. Dominant pathways: Policy and Government, Equity and Social Influences.

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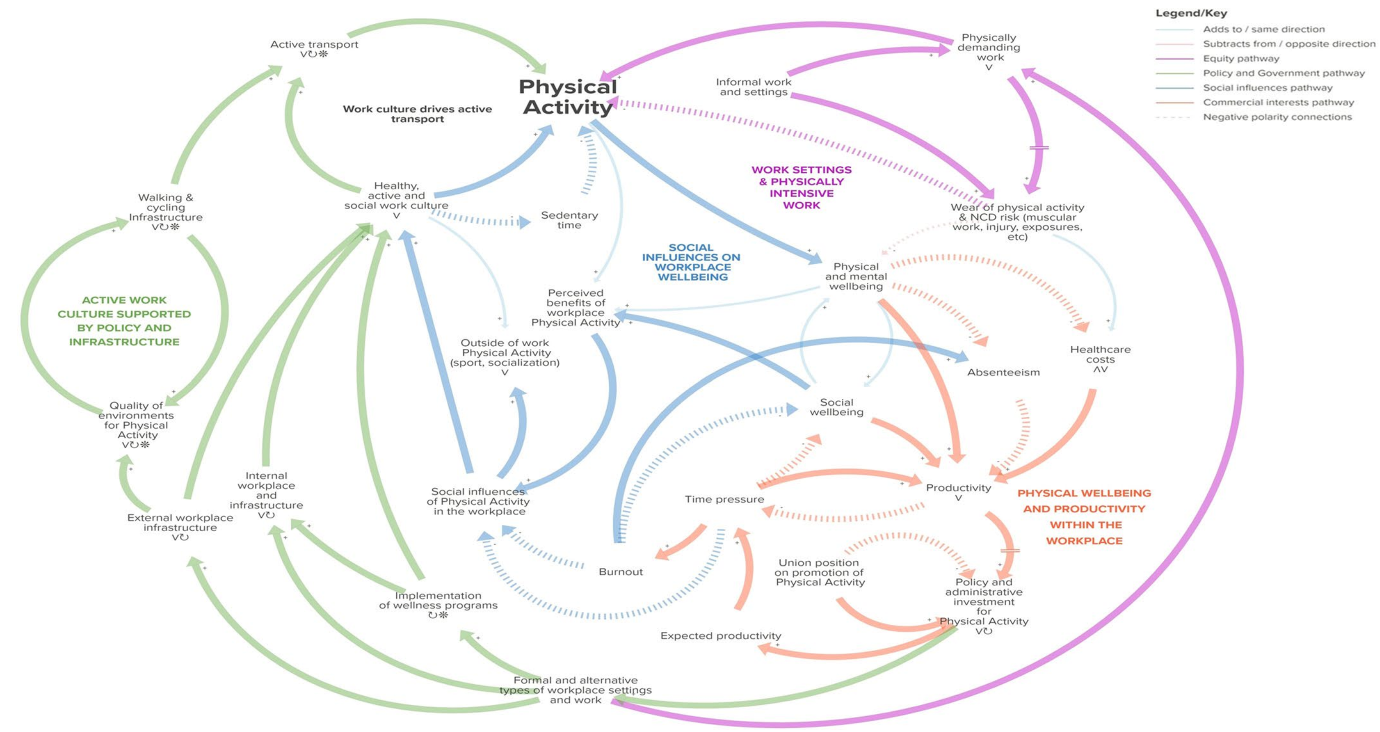

Extended Data Fig. 8 | Workplaces conceptual map. Outlines how active work culture supported by internal and external infrastructure and workplace policies increase physical activity and reduce sedentary behaviour and emissions from commuting, while enhancing employee health, wellbeing and productivity. Different work settings and physically intensive work are highlighted in relation to non-communicable disease (NCD) risk and climate vulnerability. Dominant pathways: Policy and Government, Equity and Social Influences.

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Software and code

Policy information about availability of computer code

Data collection	From January 31st to February 2nd, a multi-day exploratory group model building workshop was held in St. Louis. This workshop brought together experts specialising in the fields of physical activity, public health, climate change and system dynamics modelling (EB, RR, EH, MD, PH, TB). The primary objective of these workshops was to expose the team to a system mapping approach, grounded in systems thinking to comprehend how the “eight investments that work for physical activity “might be employed to address climate change (CC). The aim was to grasp the nuances, barriers, facilitators, potential pitfalls, and unintended consequences— all essential aspects to be considered with the goal to merge the two agendas. Recognizing the intricacies of this challenge, complexities were explored within a systemic perspective. The methodology was based on the principles and tools of System Dynamics Modelling (SDM) and group model building (GMB) predominantly using feedback as the lens to analyse the interconnections between physical activity and climate change. The SDM approach directly examines the interconnections between concrete elements such as urban infrastructure, school facilities, and motorized vehicles, and abstract factors such as perceptions, social influences, and information. Analogous to a group model building (GMB) effort, structured exercises were conducted to pinpoint variables and subsequently produce increasingly detailed qualitative diagrams. These diagrams shed light on the generic representations of a system a system, focusing on its interconnections and feedback mechanisms (Vennix, & Forrester, 1999, Hovmand, P. S., 2014). Valuable evidence and expertise concerning the "8 investments that work for physical activity" were drawn upon to initially discuss the complexity of the problem, barriers, facilitators, and other relevant aspects on the different investments. Subsequently, the facilitator reviewed basic GMB principles and presented a series of seed questions aimed at guiding the focus of variable elicitation, with consideration given to historical contexts and evolution on initiatives over time and possible social influences. A shared list of relevant factors was generated by the participants considering the previous step. Following this, participants engaged in discussions to nominate causal links or interconnections among the selected factors, articulating the mechanisms that constitute each investment.

The visual depiction of the causal structure enabled participants to elucidate the pathways through which the factors comprising each of the 8 investments exhibit synergistic or opposing relationships to Climate Change. This facilitated discussion took place during the workshop and was simultaneously transcribed into an analogical diagram, commonly referred to as a "seed structure." This representation was subsequently digitized using the Kumu platform (https://kumu.io).

Data analysis

Confidence building process
After the preliminary workshop sessions, the facilitator synthesised the data from the causal loop diagrams. In addition to these diagrams, the facilitator (EB) gathered discussion notes and session artifacts to provide a foundation for further analysis and interpretation. Once the material was systematically organised, discussions were conducted over six months with different group members, facilitated by EB. During these discussions, participants engaged in an iterative review process. This involved re-evaluating the content through expert opinions and identifying potential gaps or inaccuracies in the information conveyed in the diagram.
A key component of this review was determining whether the identified pathways were logical and sound. This extensive review and iterative feedback mechanism is termed in traditional GMB and SDM exercises the "confidence building." The confidence building process in SDM and GMB enhances the model's credibility and trustworthiness. It is an approach where confidence in a model's usefulness is built incrementally by applying various validation tests. Fundamentally, validation is integral to every stage of the modelling process, extending even to the phases of model implementation and utilization (Schwaninger and Groesser, 2020).
However, it's worth noting that the approach we undertook deviates from the traditional GMB confidence building that may engage with a broader range of stakeholders who experience and work in intervening around the issues of study. n. A cornerstone of our validation argument is the belief that experts must spearhead the foundational theories, especially those surrounding the interconnections of Physical Activity and CC Climate Change. It would be impractical and unreasonable to delegate this intricate task to the broader community and in fact at this formative stage and broad scale may be a misuse of community voice and effort.
Concluding the confidence building process, two critical sessions were held on the 20th and 21st of July 2023. These sessions were composed by the distinguished international experts in the field. During these sessions, feedback, comments, and suggestions were collected, which further refined the structures that articulate the underlying relationships between PA and CC.

Adaptations made and refining the PACC Framework
The GMB process informing the development of the PACC model was both structured and adaptive. While grounded in established system dynamics protocols, the process was modified to suit the interdisciplinary and exploratory nature of the research aim namely, to understand how physical activity investment strategies intersect with climate change mitigation, adaptation, and impact pathways.

Adaptations to standard GMB scripts: Initial discussions began with the facilitator presenting a rough conceptual framework (see figure in supplementary materials) to seed dialogue among core team members. This early sketch prompted reflection on key climate dimensions, such as extreme weather events (e.g. heat and drought), pollution, and climate migration, elements drawn from the IPCC (Intergovernmental Panel on Climate Change, 2022) and The Lancet Countdown framework (Watts 2023). Significantly, the facilitator adjusted the variable elicitation script (Luna-Reyes 2006) to broaden focus beyond traditional health determinants of physical activity, encouraging participants to explore upstream climate factors and their potential feedback with the physical activity system. Also the facilitator applied a variation of the Graphs over Time script to engage us on framing the problem and variable elicitation as a way to frame the problem to be modelled (Andersen & Richardson 1997).

Analysis of CLDs and iterative refinement: Following the initial workshop, the facilitator synthesised participant input into an analogue causal structure, which was digitised in Kumu and shared with participants for validation. Over a six-month period, the research team engaged in iterative consultations to refine this structure. Through these discussions, it became clear that conventional polarity notations (positive/negative links) in CLDs risked oversimplification and reader confusion. The group reached consensus to adopt a more narrative-based visualisation, removing polarity symbols while maintaining the depiction of reinforcing and balancing loops. This adaptation allowed greater flexibility in capturing complex interactions without overstating causality. A significant insight that emerged was the importance of distinguishing between direct and indirect contributions of the eight investment areas to climate change mitigation. For example, active transport and urban design offer clear mitigation benefits, while other strategies (e.g. workplace programmes or healthcare advice) support physical activity but do not inherently reduce emissions unless embedded within wider systemic interventions. This differentiation informed the reorganisation of the model to highlight synergistic, supportive, and catalytic roles of each investment (as presented in the lower part of the Framework Figure).

Final conceptualisation of the PACC model: Rather than aiming for a fully quantified systems map, the team reframed the output as a conceptual feedback structure, illustrating the dynamic and interconnected roles of physical activity strategies in the climate system. The agreed-upon convention was to label the loops generically as “feedback loops” to maintain explanatory clarity. This allowed the final model to serve as both a synthesis of shared understanding and a heuristic for future research and action. Finally, in October 2023, during an internal in-person peer-review meeting (5 days) that took place in Auckland, New Zealand, the model was confirmed by the wider group of academic experts (the coauthors from the 3-Paper Series).
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For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

For the case study in Denver, Colorado over June, July, and August of 2022 (92 consecutive days), we downloaded daily data on maximum air temperature from the

National Oceanic And Atmospheric Administration Climate Data Online Search Tool (URL=https://www.ncdc.noaa.gov/cdo-web/search; accessed April 21, 2023). The scoping review data were made available in the supplementary materials.

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	Forty percent of participants were female.
Reporting on race, ethnicity, or other socially relevant groupings	The GMB participants comprised a core group who developed the model (n=7) and a broader expert group of distinguished researchers who provided feedback to refine the model (n=8). The groups were internationally diverse with participant backgrounds (e.g., Australia, Brazil, Columbia, New Zealand, Mexico, Norway, USA). Forty percent of participants were female. Expertise spanned from physical activity, built environment, climate change, system dynamics modelling, urban planning and design, public health, health, health policy, epidemiology, population behavioural science, medicine, urban health, health equity, climate resilience, to environmental epidemiology.
Population characteristics	See above
Recruitment	This project was explicitly focused on convening experts and scholars in the fields of physical activity and climate change research. Participants were purposively selected based on their recognised expertise and leadership in the fields of physical activity, public health, climate change, and systems science, particularly system dynamics modelling. Recruitment was guided by the principle of assembling a diverse group of thought leaders capable of contributing deep disciplinary knowledge while engaging in transdisciplinary dialogue. Individuals were identified through professional networks, existing collaborations, and their scholarly contributions to their respective fields. This purposive sampling ensured that the workshop included participants with the capacity to critically engage with complex systems thinking and contribute to the co-construction of a shared model integrating the physical activity and climate change agendas. The research team was comprised for a core group (n=7) and a broader expert group of researchers (n=10).
Ethics oversight	All participants were academic collaborators who contributed as part of their professional roles. We had consulted with the ethics office and we were advised that no approval was required. No primary data were collected from human participants external to the research team, and the process did not involve collection of identifiable personal information, behavioural interventions, or outcomes research. Therefore, ethics approval was not sought, as the activity did not fall within the scope of human participant research requiring institutional ethics review under the relevant national and institutional guidelines. The GMB workshop and subsequent sessions were part of a co-authorship and co-creation process focused on systems conceptualisation. All contributors participated voluntarily and with full awareness of the project's aims, and all are acknowledged as co-authors on the resulting publication.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

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Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	This study was observational in nature and used population-level, passively collected data rather than individual participant recruitment. The sample size was determined by the availability of complete daily temperature data and bicycle use data for the study period. We analysed 92 consecutive days (June–August 2022) using daily weather data on maximum air temperature from the National Oceanic And Atmospheric Administration Climate Data Online Search Tool (URL=https://www.ncdc.noaa.gov/cdo-web/search; accessed April 21, 2023). Of the 37 stations present in the downloaded dataset from the City and County of Denver (henceforth, Denver), 3 had no missing data on maximum temperature during this time period. We used measurements from the Denver Water Department (station ID= USC00052223) because of its central location in Denver. We gathered daily data (called "daily summaries" in the online tool) at this location on maximum temperature and amount of precipitation. To measure bicycling, we used data from Strava Metro. Strava is an app used by about 5%-15% of bicyclists to track their activities. Strava makes their data available via Strava Metro to qualifying organizations in an anonymized format. We obtained the number of rides observed on every segment of street and trail in the study area (n= 251,068 segments) on every day in June, July, and August of 2022. We calculated bicycle-distance ridden on these segments by multiplying the number of rides on the segment by the segment's length. We then summed that bicycle-distance over all segments by month for a monthly total. Although no formal power calculation was performed due to the ecological nature of the study, the breadth of spatial and temporal data, combined with full coverage of the summer period, provides a robust basis for identifying patterns in bicycling behaviour relative to heat exposure. This volume of data is sufficient to support exploratory analysis of associations and behavioural adaptations to climatic extremes.
Data exclusions	Inclusion of available data as described above.

Replication	We described the methods and analysis in enough detail in the Methods section of the main manuscript for future replication.
Randomization	Randomisation not relevant to this study as it is a quasi-experimental study, we estimate the effect of extreme heat on observed bicycling in the Denver area
Blinding	Blinding not relevant to this study as it is a quasi-experimental study, we estimate the effect of extreme heat on observed bicycling in the Denver area

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Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	NA
Novel plant genotypes	NA
Authentication	NA