Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

# Integrating health and climate resilience in Brazil's largest social housing program: A community-based system dynamics approach applied to Minha Casa, Minha Vida

Ana Luiza Favarão Leão
analuiza@wustl.edu
Washington University in St. Louis
Milena Franco Silva
Washington University in St. Louis
Guilherme Stefano Goulardins
Universidade de São Paulo
Alexandre Augusto de Paula da Silva
Washington University in St. Louis
Yi Wang
Washington University in St. Louis
Maryse Rios-Hernandez
Washington University in St. Louis
Alessandro Lunelli
Pontifícia Universidade Católica do Paraná
Paulo Nascimento Neto
Pontifícia Universidade Católica do Paraná
Alex Antônio Florindo
Universidade de São Paulo
Rodrigo Siqueira Reis
Washington University in St. Louis

Research Article

Keywords: Group Model Building, causal loop diagram, social housing, climate resilience, health equity, Brazil, Minha Casa, Minha Vida

Posted Date: April 20th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9041181/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

## Abstract

Climate change impacts and health inequities intersect sharply in Brazil's social housing, where housing location, design, and governance shape residents' exposure to environmental hazards and everyday wellbeing. Yet housing, health, and climate agendas often operate in parallel, limiting integrated policy responses for low-income residents of the Minha Casa, Minha Vida (MCMV) Faixa 1 program. This study used Group Model Building (GMB) to co-develop a causal loop diagram (CLD) mapping interactions among housing, health, and climate resilience in MCMV Faixa 1 and to identify leverage points for equitable, climate-resilient policy and practice. We conducted a two-day, in-person GMB workshop in São Paulo (August 2025) with 18 participants (11 external experts and 7 research team members) representing public health, architecture, urban planning, geography, nutrition, and social policy. Structured facilitation scripts were used to identify system variables and relationships, which were synthesized into a CLD and iteratively refined through documentation review and participant validation. The resulting CLD included 35 variables across three domains: health (n = 7), climate resilience (n = 8), and broader social and governance influences (n = 20). Income inequality by race and gender emerged as the most structurally central variable, bridging social, environmental, and policy subsystems. Adaptive urban design and climate-oriented policy implementation also showed high connectivity, linking built-environment interventions to health and resilience outcomes. Reinforcing dynamics connected resilient housing quality, adaptive urban design, and social participation to improvements in wellbeing and adaptive capacity, while balancing dynamics reflected constraints associated with socioeconomic inequality, peripheralization, and urban violence. Leverage points clustered around six areas: integrated housing design standards, urban greening and nature-based solutions, active mobility and low-carbon transport connectivity, participatory governance, intersectoral policy coordination, and integrated monitoring systems. These findings highlight actionable policy levers to support more equitable and climate-resilient housing strategies within the MCMV program.

## Introduction

Climate change is intensifying environmental stressors and amplifying existing social and health inequities across cities worldwide (Nieuwenhuijsen, 2024). Rising temperatures, heatwaves, floods, and storms are increasingly disrupting urban systems, exposing populations to physical, social, and economic vulnerabilities that threaten both immediate and long-term well-being (Romanello et al., 2023). The health impacts of these changes are multifaceted, encompassing the widespread occurrence of vector-borne diseases (Madeleine C Thomson & Lawrence R Stanberry, 2022), increased cardiovascular and respiratory risks (Rocque et al., 2021; Silveira Ismael H. AND Cortes, 2023), and heightened mental health challenges (Corvetto et al., 2023). In cities, the built environment concentrates exposure to these hazards, particularly in areas characterized by precarious housing, inadequate infrastructure, and limited access to green and blue spaces. Housing thus stands at the intersection of urban health and climate resilience, functioning simultaneously as a site of exposure, protection, and recovery (Bezgrebelna et al., 2021; Li et al., 2025; McKee et al., 2026).

Access to adequate, secure, and well-located housing is increasingly recognized as both a social determinant of health and a cornerstone of climate resilience (Li et al., 2025; McKee et al., 2026; Rolfe et al., 2020). Affordable housing can mitigate environmental risks by improving structural quality, thermal comfort, and energy efficiency, while also supporting mental health, stability, and social cohesion (Bentley et al., 2023; Hamilton et al., n.d.; Maidment et al., 2014). When integrated into well-connected and resource-rich urban areas, it facilitates access to employment, education, mobility, and opportunities for active living, factors consistently associated with improved population health and reduced inequities (Diez Roux & Mair, 2010; Ludwig et al., 2012; Mindell & Watkins, 2024). Conversely, poorly located or inadequately designed housing can reinforce segregation, deepen vulnerability to climate extremes, and perpetuate cycles of poverty and illness (Arcaya et al., 2016; Berberian et al., 2022; Kephart et al., 2025). Framed through a systems and sustainability lens, these contrasting pathways underscore housing not merely as shelter, but as structural infrastructure that simultaneously shapes health trajectories, distributional equity, and adaptive capacity; core domains reflected in SDG 3 (Good Health and Well-Being), SDG 10 (Reduced Inequalities), and SDG 13 (Climate Action) of the United Nations agenda (UN General Assembly, 2015).

In Brazil, the relationship between housing, health, and inequality has long been shaped by historical patterns of urbanization marked by spatial segregation and the persistence of informal settlements (Monteiro & Veras, 2017). In 2009, the federal government launched the *Minha Casa, Minha Vida* (MCMV) program (Law 11.977, 2009), one of the world's largest social housing initiatives (Júnia Santa Rosa, 2015), to address the country's housing deficit through large-scale construction of subsidized or financed units to low- and middle-income families (Cardoso, 2013). Between 2009 and 2020, MCMV delivered over six million homes and generated millions of jobs (CMAP, 2020), representing a major investment in social infrastructure. After a temporary interruption in 2020, the program was reinstated in 2023 with renewed targets emphasizing sustainability, social inclusion, and housing infrastructure for climate adaptation (Ministério das Cidades, 2023). This renewed phase presents a critical opportunity to align housing policy with health and environmental resilience goals (Ministério das Cidades, 2023).

Despite its scale and policy relevance, there is limited evidence on how the MCMV program influences residents' health, well-being, and climate resilience (Silva et al., 2026). Existing evaluations have largely focused on economic indicators or construction outputs, often overlooking residents' lived experiences and the intersectoral mechanisms linking housing, health, and climate resilience (Acolin et al., 2019; Muianga & Kowaltowski, 2024).The absence of integrated frameworks constrains the design of policies capable of addressing systemic inequities and managing the compound risks faced by low-income populations in a changing climate (Romanello et al., 2023;

Rutter, 2017). This fragmentation reflects how housing, health, and climate agendas have historically evolved in parallel, despite their shared influence on urban well-being.

Recent applications of systems-thinking approaches in public health and urban research have demonstrated the utility of participatory modeling for examining the interconnections between environmental, social, and policy systems (Langellier et al., 2019). Building on this evidence, the present study applies the Group Model Building (GMB) methodology to the housing–health–climate nexus in Brazil's MCMV Faixa 1 program, the program's tier serving the lowest-income households. GMB is a participatory systems method that elicits and structures collective expertise to represent complex problems through causal relationships and feedback mechanisms (Rouwette et al., 2002). It supports the identification of dynamic pathways and potential intervention leverage points across sectors (Hovmand, 2014). In this study, GMB was used to co-develop a causal loop diagram (CLD) that represents the interactions among housing conditions, health outcomes, and climate-resilience factors in the MCMV Faixa 1 context.

The goal of this paper is to describe the process and methodological application of GMB to a social-housing system, detailing how stakeholder knowledge was integrated to conceptualize the feedback structure connecting housing, health, and climate resilience. Specifically, we aim to (1) map the perceived causal relationships among key determinants of health and climate resilience in MCMV Faixa 1 developments; and (2) identify system components and leverage points that can inform the design of more equitable and climate-resilient housing policies in Brazil.

# Methods

## Study design

This study employed a GMB approach, a participatory method derived from system dynamics, to explore the interconnections between housing, health, and climate resilience in Brazil's MCMV Faixa 1 program. GMB engages participants in collectively identifying variables, mapping causal relationships, and developing feedback structures that explain complex system behavior. The method follows established procedures in participatory system dynamics and draws on scripts and guidance from Scriptapedia (Hovmand et al., 2014), which standardize facilitation steps, data capture, and reflection processes.

This GMB workshop was designed to elicit expert knowledge of the mechanisms linking health and climate resilience within affordable-housing systems and to identify policy-relevant leverage points to improve equity and climate resilience outcomes. The study design was informed by prior applications of system dynamics modeling in urban health research (e.g., Pirani et al., 2022; Nogueira et al., 2024; Favarão Leão et al., 2024).

## Participants

A total of 18 participants took part in the GMB process, including 11 external experts and 7 members of the research team. IRB approval was obtained in both Brazil (CAAE: 87845925.6.0000.0020) and the United States, and informed consent was obtained from all participants. Participants represented a range of disciplines, such as architecture, urban planning, public health, geography, nutrition, and social policy, and sectors including academia, advocacy, and policy, ensuring a multidimensional perspective on housing, health, and climate resilience. External participants were recruited through purposive sampling based on prior collaborations and their academic or professional experience with the Minha Casa, Minha Vida (MCMV) program, social housing, or climate resilience in urban contexts. Selection also considered gender balance, regional diversity, and professional seniority. Participants were affiliated with institutions in São Paulo, Curitiba, and Londrina and received background information about the project before providing informed consent. The facilitation team comprised professionals with complementary expertise in systems thinking, public health, urban planning, and urban design. Further details on participant characteristics are provided in Supplementary Table S1.

## Workshop structure

We implemented the GMB process through a two-day, in-person workshop held at the University of São Paulo's School of Public Health (São Paulo, Brazil) on August 20–21, 2025. The in-person sessions were complemented by pre-workshop planning calls and post-workshop online validation activities.

Day 1 engaged all participants (n = 18) in a sequence of scripted activities: Hopes & Fears, used to surface stakeholder expectations and concerns; Graphs Over Time, which explored how key issues related to health and climate resilience evolve over time; Variable Elicitation, aimed at identifying key factors shaping the system; Dot Voting, used to prioritize the most relevant variables; and Connection Circles, a participatory mapping exercise used to identify causal relationships among prioritized variables. The outputs of these activities culminated in a first draft of a causal loop diagram (CLD), visualized in Kumu, an online platform for systems mapping (Kumu, 2024).

Day 2 focused on technical refinement and model revision with a smaller expert group (n = 7), including validation of variable definitions, causal polarities, and linkages, as well as discussion of potential leverage points using an impact × feasibility lens. A detailed facilitation manual, full workshop agenda, and the scripts used to achieve the workshop objectives and outputs are provided in the Supplementary Material.

### Post-workshop validation and confidence-building

Following the in-person GMB workshop, all participants were invited by email to review the consolidated CLD via a Qualtrics survey as part of a confidence-building process. The survey link was distributed on Aug 22, 2025, with responses requested by Sept 3, 2025. Participants could respond asynchronously and provide free-text justifications; responses were not anonymous to allow targeted clarification when needed. The survey asked respondents to assess whether (i) any essential elements were missing from the model, (ii) any existing connections were strongly disagreed with, and (iii) any additional connections should be included.

Submissions were reviewed independently by two team members (ALS and AAS) who coded suggestions against the working variable list and link set, flagged conflicts, and documented proposed revisions with rationale. Revisions that improved structural coherence (clear variable definitions, unambiguous polarity), conceptual validity (alignment with stakeholder expertise and literature), and parsimony (removal of redundancies) were incorporated into the Kumu model, with a visible version log (pre- and post-survey). When comments conflicted, the team applied a deliberative rule: retain original structure unless the proposed change (i) had cross-comment convergence or (ii) resolved an acknowledged ambiguity from the in-person sessions. This procedure follows confidence-building principles in system dynamics, emphasizing stakeholder consensus and conceptual robustness rather than quantitative calibration.

### Data collection and analysis

Multiple qualitative data sources were collected: facilitator/observer field notes, photographs of wall charts and worksheets, and digital artifacts (Kumu versions). Notes were transcribed and thematically coded to classify variables and relationships into the Health, Climate Resilience, and Influences domains (with subcodes for built/environmental, social/economic, and governance/policy). The initial CLD from Day 2 was then iteratively refined through (i) a brief online review session and (ii) the Qualtrics survey. Post-survey edits and justifications were recorded in a change log, and final face validity was confirmed in a short follow-up meeting with the core facilitation team.

### Ethical considerations

This study was conducted in accordance with national and institutional ethical standards. Ethical approval was obtained from the Pontifícia Universidade Católica do Paraná (PUCPR) under the protocol CAAE 87845925.6.0000.0020. All participants received written information about the study objectives, procedures, and data use, and provided informed consent before participation.

## Results

### Common understanding of the system

The final causal loop diagram (CLD) co-developed during the workshop contained 35 variables distributed across three thematic domains (*Supplementary* Figure S1 and *Table S2*):

1. Health (7 variables) – *physical activity for leisure and transport, access to health services, food and nutrition security, mental health, chronic and infectious diseases*.
2. Climate resilience (8 variables) – *resilient housing quality and comfort, adaptive urban design, resilient housing policies, capacity to respond to climate events, low-carbon public transport, and implementation of climate-oriented policies*.
3. Urban systems and structural conditions (20 variables) – spanning built-environment, social-economic, and governance factors such as *land cost, location of housing developments, vegetation cover, air pollution, active-mobility infrastructure, social networks, income inequality by race and gender, safety and violence, political participation, and financial resources*.

These variables describe a multilevel system in which health and climate outcomes emerge from interactions among housing design, environmental exposures, governance capacity, and persistent socioeconomic inequalities. Within this network, several variables occupied structurally prominent positions as connectors across domains, linking social conditions, built-environment factors, and policy processes. Income inequality by race and gender was the most connected element in the system, showing the highest degree and betweenness centrality, indicating its pervasive influence and its bridging role between socioeconomic conditions, exposure pathways, and governance and policy subsystems. Adaptive urban design coverage and the implementation of climate-oriented public policies also displayed high degree and closeness scores, suggesting they can rapidly propagate effects throughout the system by linking built-environment interventions to health-relevant pathways such as mobility, air quality, and public space use. Additional connector variables included access to essential public services and the implementation of resilient housing policies, which functioned as integrators connecting infrastructure and service provision to housing conditions and downstream health and resilience outcomes. Together, these structural features highlight the diagram’s emphasis on cross-domain coupling between structural inequality, adaptive urban form, and policy implementation as key pathways shaping health and climate resilience in MCMV Faixa 1.Feedback mechanisms: reinforcing and balancing dynamics

The CLD revealed multiple reinforcing and balancing feedbacks describing how housing, health, and climate resilience interact within MCMV Faixa 1. We summarize the most salient mechanisms below (see Supplementary Figure S1 for summarized CLD structure).

Some reinforcing feedbacks were particularly prominent along with balancing feedbacks that highlighted constraints that can dampen or offset gains:

1. Resilient Housing and Well-Being: Improvements in construction quality and environmental comfort (e.g., thermal comfort) were linked to better mental and physical health, which, in turn, increased demand for and support of resilient housing standards and continued investment in housing quality.
2. Adaptive Urban Design and Active Mobility: Increases in adaptive urban design (e.g., green infrastructure, shading/trees, and safe parks and plazas) were linked to greater opportunities for physical activity and mobility, improvements in air quality and environmental comfort, and stronger social cohesion, reinforcing support for further improvements in public space and neighborhood design.
3. Policy Integration and Institutional Learning: Social participation and public pressure were linked to stronger implementation of housing and climate policies and improved adaptive capacity, reinforcing trust and momentum for coordinated governance and policy integration.
4. Socioeconomic Inequality and Exposure: Income inequality by race and gender constrained vulerable groups' access to secure, well-located housing and resources, reinforcing their exposure to hazards and health risks and limiting residents' ability to benefit from protective housing and neighborhood conditions.
5. Market Pressure and Peripheralization: Rising land costs and market pressures in central locations were linked to the displacement and peripheralization of low-income households, reducing access to services and opportunities and increasing exposure to environmental risks—counteracting potential benefits from improvements in housing policy and design.
6. Urban Violence and Behavioral Constraint: Insecurity in public and domestic spaces was linked to reduced use of public spaces and fewer opportunities for leisure-time physical activity, weakening social cohesion and dampening potential health gains from neighborhood improvements.

Leverage points identified through the GMB process clustered around six areas: (i) health- and climate-integrated housing design standards; (ii) urban greening and nature-based solutions; (iii) active mobility infrastructure and low-carbon transport connectivity; (iv) participatory governance and co-management mechanisms; (v) intersectoral coordination and financing across housing, health, and climate portfolios; and (vi) integrated data systems for monitoring exposures, service access, safety, and health outcomes. These leverage clusters map onto the major feedback mechanisms described above and provide a structured basis for considering coordinated policy and practice responses in MCMV Faixa 1.

## Discussion

Using GMB, we mapped the perceived causal relationships among key determinants of health and climate resilience in MCMV Faixa 1 developments, identifying components and leverage points of the system. This GMB process surfaced a coherent theory of change: health and climate resilience in MCMV Faixa 1 are co-produced through feedback between (i) housing quality/comfort, (ii) adaptive urban design enabling mobility and reducing exposure to climate risks, and (iii) governance capacity shaped by participation and cross-sector coordination. At the same time, the model highlights constraining dynamics, particularly structural inequality, market-driven peripheralization, and violence/insecurity, that can dampen or reverse gains by limiting access to protective environments and undermining safe use of neighborhood resources. These reinforcing and balancing feedbacks depict a system in which progress toward health and climate resilience depends on simultaneous shifts in housing quality, neighborhood form, service access, and governance, while structural inequality, market dynamics, and violence can limit or reverse gains.

The produced CLD highlights a reinforcing mechanism in which resilient housing quality and environmental comfort (e.g., thermal comfort and protection from climate stressors) contribute to improved mental and physical health, which, in turn, increases social demand and political support for resilient housing standards and sustained investment. In CLD terms, housing is not a static "exposure container" but an active leverage that shapes downstream health pathways and feeds back into policy and resource allocation. This matters for urban health equity because Faixa 1 households face disproportionate climate-related stressors and structural barriers to protective housing conditions; small deficits in comfort and resilience (heat exposure, dampness, poor ventilation, insecure maintenance) can cascade into mental distress, chronic disease risk, and reduced capacity to cope with shocks, thereby widening inequities (Flores-Ortiz et al., 2023; Liu et al., 2022). Prior research on housing as a social determinant of health has documented associations between housing quality, energy insecurity, psychosocial stress, and health outcomes, while climate adaptation scholarship has increasingly emphasized the home as a frontline site of risk reduction (Li et al., 2025). By making explicit the feedback between improved housing conditions, perceived wellbeing, and collective pressure for housing standards and policy enforcement, this mechanism illustrates how resilience-oriented housing investments can simultaneously advance health promotion, reduce structural inequalities, and strengthen climate adaptation, which are objectives central to SDGs 3, 10, and 13 of the United Nations Sustainable Development Goals framework.

A second reinforcing pathway connects adaptive urban design coverage, including greening, shading, and safe, usable public spaces, to increases in active mobility and physical activity, improved air quality and environmental comfort, and stronger social cohesion. In the CLD, these components operate as a coupled "co-benefits" engine: climate-responsive urban form reduces exposure (heat, pollution) while simultaneously enabling health-promoting behaviors, and the resulting visible benefits can reinforce public and institutional

support for further neighborhood investment. This mechanism is central to urban health equity because the benefits of green infrastructure, safe parks, and continuous walking/cycling networks are unevenly distributed across cities, and residents of peripheral or under-served social housing developments often experience the worst combination of limited amenities, higher environmental burdens, and constrained mobility options (Rigolon et al., 2021). The mechanism aligns with evidence linking green/blue space access, walkability, and safe public realms to physical activity, cardiometabolic and mental health outcomes, and reduced heat and pollution exposure (Gascon et al., 2015; Nieuwenhuijsen, 2024; Sallis et al., 2016). Framed within the SDG agenda (UN General Assembly, 2015), this pathway operationalizes climate action (SDG 13) through spatial adaptation strategies that generate direct health gains (SDG 3) while addressing inequitable environmental burdens and access to amenities (SDG 10). It also extends climate adaptation and nature-based solutions literatures by situating these strategies within the lived realities of social housing environments, where safety, maintenance, and connectivity determine whether “green” investments translate into actual exposure reduction and behavior change, especially for women, older adults, and other groups differentially affected by insecurity and mobility constraints (Kabisch et al., 2017).

A third mechanism emphasizes governance: social participation and public pressure strengthen the implementation of housing- and climate-oriented policies, thereby enhancing adaptive capacity and building trust, reinforcing continued engagement and cross-sector coordination. In CLD terms, participation is not only a procedural value; it is a functional driver that influences whether policies are executed, maintained, and iteratively improved. This matters for urban health equity because fragmented governance and weak accountability can reproduce inequities even when policies nominally incorporate health or climate goals; marginalized groups often bear disproportionate impacts of climate change while having the least institutional voice, and trust deficits can reduce uptake of services and weaken collective action (Mearns & Norton, 2009). The loop aligns with literatures on governance for health equity, participatory planning, and adaptive climate governance, which show that durable outcomes often depend on coordination across sectors, legitimacy, and learning-oriented institutions (Franco Silva et al., 2026; Howlett, 2009; Peters, 2018). Within the SDG framework, this governance feedback loop functions as the institutional backbone that enables sustained progress toward health, equity, and climate goals, ensuring that advances in housing and urban design are not episodic but embedded in accountable and adaptive systems. The obtained results extend this work by positioning institutional learning as a feedback process tied to the everyday conditions of social housing (maintenance, safety, service access), implying that integrated housing–health–climate agendas are more likely to persist when participation is formalized (e.g., co-management channels, transparent monitoring) and when implementation capacity is supported through stable financing and interministerial alignment (Breuer et al., 2023).

Our findings point to coordinated policy rather than isolated fixes. First, embed health- and climate-responsive design standards in social-housing specifications, covering thermal comfort, ventilation, shading, materials, and flood/heat readiness. Complement this with urban greening and nature-based solutions within and around MCMV complexes (street trees, shaded corridors, and safe, inclusive parks and plazas) to lower heat and pollution while enabling active living. Strengthen active mobility and low-carbon transport through continuous sidewalks, protected cycling networks, and high-quality public transit linking housing to jobs and services, thereby reducing exposure and noncommunicable disease risk. Institutionalize participatory and co-management mechanisms so residents have formal channels to sustain maintenance, safety, and adaptive actions, and align interministerial mandates and financing across Cities, Health, and Environment portfolios using shared criteria and joint monitoring. Finally, build integrated data systems that routinely track thermal comfort, environmental exposure, service access, safety, physical activity, and morbidity within housing programs. Together, these actions amplify the system’s virtuous feedbacks and weaken constraining dynamics, particularly inequality, peripheralization, and violence, thereby increasing the likelihood of durable effects.

GMB was well-suited to this context because MCMV Faixa 1 operates through interdependent systems—housing standards, neighborhood design, service access, and multi-level governance—where health and resilience emerge from their interaction. The CLD produced through GMB captures these interdependencies by identifying feedback loops and cross-domain connectors, offering a transparent account of why benefits may accumulate in some conditions and stall in others. Conventional evaluations often measure outputs (units delivered, costs) or a narrow set of outcomes, without representing the dynamic pathways that link policy implementation and environmental exposure. The CLD fills this gap by organizing stakeholder knowledge into testable mechanism pathways for future mixed-methods and quantitative work.

At the same time, the CLD should be interpreted as a qualitative, hypothesis-generating model rather than an estimate of causal effects. The workshop involved a small, expert-leaning sample, and resident perspectives were not included; incorporating residents is essential for construct validity, boundary critique, and equity in problem framing. In addition, the model reflects a specific policy window and workshop context; its transferability should be assessed across regions and across cycles of MCMV implementation. Finally, we did not quantify parameters, estimate effect sizes, or simulate scenarios, so the mapped relationships and leverage points are best viewed as plausible mechanisms requiring empirical testing and iterative refinement.

These limitations also point to priorities for future research. First, future studies could conduct resident-inclusive cycles of model refinement across multiple MCMV settings to assess whether the key variables and feedback structures identified here align with residents’ lived experiences and to identify context-specific mechanisms. Second, quantitative follow-up studies could evaluate priority pathways, particularly those related to siting, design standards, and transport connectivity, using complementary approaches such as stock-and-flow system dynamics to explore policy scenarios and DAG-informed observational analyses to strengthen causal inference where policy changes or natural experiments permit. Third, regional replications may help examine heterogeneity across climate zones, metropolitan contexts, and implementation arrangements. Finally, future work could translate CLD elements into practical monitoring

frameworks by embedding indicators (e.g., thermal comfort, environmental exposures, service access, safety, mobility, and health outcomes) into program tracking systems, enabling iterative learning and policy adjustment over time.

## Conclusion

Using GMB, we developed a qualitative systems account of how housing design and siting, social and service infrastructure, and governance arrangements interact to shape health and climate resilience in MCMV Faixa 1. The CLD, comprising 35 variables across health, climate resilience, and broader social and governance influences, highlighted how structural inequalities, adaptive urban design, and policy implementation act as central connectors linking housing conditions to downstream health and resilience outcomes. Reinforcing feedbacks related to resilient housing quality, adaptive urban design, and policy integration illustrated pathways through which improvements in housing and neighborhood environments can generate cumulative health and resilience benefits. At the same time, balancing dynamics associated with socioeconomic inequality, market-driven peripheralization, and urban violence revealed structural constraints that can limit or offset potential gains.

Within this system, leverage points identified through the GMB process clustered around six areas spanning housing design, neighborhood environment, mobility infrastructure, participatory governance, intersectoral policy coordination, and integrated monitoring systems. These clusters align with the key feedback mechanisms identified in the CLD and highlight opportunities for coordinated policy responses that link housing, health, and climate resilience within MCMV Faixa 1.

Advancing resilience in affordable housing will require longitudinal, participatory, and data-integrated approaches. Future researh and practice priorities include routine monitoring of health and climate resilience indicators within housing programs, and prospective evaluation of coordinated policy packages using simulation and quasi-experimental designs. By integrating housing, health, and climate agendas through systems-informed approaches, social housing programs such as MCMV can move beyond isolated interventions toward strategies capable of producing sustained and equitable improvements in urban health and climate resilience.

## Declarations

**Clinical trial number**: not applicable.

**Human ethics and consent to participate declarations:** IRB approval was obtained in both Brazil (CAAE: 87845925.6.0000.0020) and the United States, and informed consent was obtained from all participants.

**Acknowledgments and Funding Declaration:** This work was supported by the Global Incubator Grant at Washington University in St. Louis. This publication was also supported in part as a Washington University in St. Louis Center for the Study of Race, Ethnicity & Equity Small Grant. We also acknowledge the Prevention Research Center at the School of Public Health, Washington University in St. Louis, for its institutional support of this research. We are deeply grateful to all external contributors whose insights, expertise, and constructive debate shaped the development of the causal loop diagram. We especially thank the participants who brought direct experience with Minha Casa, Minha Vida (MCMV) developments and enriched the discussions with practical and contextual knowledge. We also appreciate the colleagues who participated in the post-workshop validation process and provided thoughtful comments through the online review. Their feedback strengthened the clarity, coherence, and rigor of the final model.

# Author Contribution

A.L.F.L. conceived the study, led the design of the research, coordinated the project, facilitated and conducted the workshop, performed the analysis, and wrote the main manuscript.M.F.S. contributed to the planning of the study and reviewed the manuscript.G.S.G. contributed to study planning, supported the IRB approval process, participated in the workshop, and reviewed the manuscript.A.A.P.S. contributed to the planning of the workshop, participated in the workshop, and reviewed the manuscript.Y.W. participated in the workshop and reviewed the manuscript.M.R.-H. contributed to project coordination and reviewed the manuscript.A.L. participated in the workshop and reviewed the manuscript.P.N.N. provided senior guidance on the research design and reviewed the manuscript.A.A.F. provided senior guidance on the research design and reviewed the manuscript.R.S.R. contributed to the conception of the study, supervised the research process, and reviewed the manuscript.All authors reviewed and approved the final manuscript.

## References

1. Arcaya, M. C., Tucker-Seeley, R. D., Kim, R., Schnake-Mahl, A., So, M., & Subramanian, S. V. (2016). Research on neighborhood effects on health in the United States: A systematic review of study characteristics. In *Social Science and Medicine* (Vol. 168, pp. 16–29). Elsevier Ltd. https://doi.org/10.1016/j.socscimed.2016.08.047
2. Bentley, R., Daniel, L., Li, Y., Baker, E., & Li, A. (2023). *The effect of energy poverty on mental health, cardiovascular disease and respiratory health: a longitudinal analysis*. www.thelancet.com
3. Berberian, A. G., Gonzalez, D. J. X., & Cushing, L. J. (2022). Racial Disparities in Climate Change-Related Health Effects in the United States. In *Current Environmental Health Reports* (Vol. 9, Number 3, pp. 451–464). Springer Science and Business Media

Deutschland GmbH. https://doi.org/10.1007/s40572-022-00360-w

4. Bezgrebelna, M., McKenzie, K., Wells, S., Ravindran, A., Kral, M., Christensen, J., Stergiopoulos, V., Gaetz, S., & Kidd, S. A. (2021). Climate change, weather, housing precarity, and homelessness: A systematic review of reviews. In *International Journal of Environmental Research and Public Health* (Vol. 18, Number 11). MDPI AG. https://doi.org/10.3390/ijerph18115812
5. Cardoso, A. L. (2013). *O Programa Minha Casa Minha Vida e seus Efeitos Territoriais* (João Baptista Pinto, Ed.). Letra Capital.
6. CMAP, C. de monitoramento e avaliação de políticas públicas. (2020). *Relatório de Avaliação Programa Minha Casa, Minha Vida*. https://www.gov.br/economia/pt-br/acesso-a-
7. Corvetto, J. F., Helou, A. Y., Dambach, P., Müller, T., & Sauerborn, R. (2023). A Systematic Literature Review of the Impact of Climate Change on the Global Demand for Psychiatric Services. In *International Journal of Environmental Research and Public Health* (Vol. 20, Number 2). MDPI. https://doi.org/10.3390/ijerph20021190
8. Diez Roux, A. V., & Mair, C. (2010). Neighborhoods and health. In *Annals of the New York Academy of Sciences* (Vol. 1186, pp. 125–145). https://doi.org/10.1111/j.1749-6632.2009.05333.x
9. Hamilton, I., Milner, J., Chalabi, Z. , D. P., Jones, B., Shrubsole, C., Davies, M., & Wilkinson, P. (n.d.). Health effects of home energy efficiency interventions in England: a modelling study. *BMJ Open*, *4*(5), e007298. https://doi.org/https://doi.org/10.1136/bmjopen-2014-007298
10. Júnia Santa Rosa. (2015). Directory of institutional development and Technical cooperation foreword. In Christine Whitehead, Fernando Garcia de Freitas, Júnia Santa Rosa, & Anacláudia Rossbach (Eds.), *Dialogue Brazil and European Union: social housing, finance and subsidies* (pp. 1–176). Ministry of Cities.
11. Kephart, J. L., Bilal, U., Gouveia, N., Sarmiento, O. L., Shingara, E., Rangel Moreno, K., Bakhtsiyarava, M., Rodriguez, J. P., Ayala, S., Carrasco-Escobar, G., & Diez Roux, A. V. (2025). Social disparities in neighborhood flood exposure in 44,698 urban neighborhoods in Latin America. *Nature Cities*, *2*(3), 246–253. https://doi.org/10.1038/s44284-025-00203-3
12. Law 11.977, Pub. L. 11.977 (2009).
13. Li, A., Toll, M., Chapman, R., Howden-Chapman, P., Hernández, D., Samuelson, H., Woodward, A., & Bentley, R. (2025). Housing at the intersection of health and climate change. In *The Lancet Public Health* (Vol. 10, Number 10, pp. e865–e873). Elsevier Ltd. https://doi.org/10.1016/S2468-2667(25)00141-0
14. Ludwig, J., Duncan, G. J., Gennetian, L. A., Katz, L. F., Kessler, R. C., Kling, J. R., & Sanbonmatsu, L. (2012). Neighborhood effects on the long-term well-being of low-income adults. *Science*, *337*(6101), 1505–1510. https://doi.org/10.1126/science.1224648
15. Madeleine C Thomson, & Lawrence R Stanberry. (2022). Climate Change and Vectorborne Diseases. *The New England Journal of Medicine*, (387), 1969–1978. https://doi.org/https://doi.org/10.1056/NEJMra2200092
16. Maidment, C. D., Jones, C. R., Webb, T. L., Hathway, E. A., & Gilbertson, J. M. (2014). The impact of household energy efficiency measures on health: A meta-analysis. *Energy Policy*, *65*, 583–593. https://doi.org/https://doi.org/10.1016/j.enpol.2013.10.054
17. McKee, M., Howden-Chapman, P., Braithwaite, I., & Bentley, R. (2026). Health-promoting housing policy in a changing climate: integrating affordability, security, and resilience. In *Health Promotion International* (Vol. 41, Number 1). Oxford University Press. https://doi.org/10.1093/heapro/daaf238
18. Mindell, J. S., & Watkins, S. J. (2024). Transport, health and inequality. An overview of current evidence. *Journal of Transport and Health*, *38*. https://doi.org/10.1016/j.jth.2024.101886
19. Ministério das Cidades. (2023). *LEI N$^{o}$ 14.620, DE 13 DE JULHO DE 2023*.
20. Monteiro, A. R., & Veras, A. T. de R. (2017). The housing issue in Brazil. *Mercator*, *16*(7), 1–12. https://doi.org/10.4215/rm2017.e16015
21. Rocque, R. J., Beaudoin, C., Ndjaboue, R., Cameron, L., Poirier-Bergeron, L., Poulin-Rheault, R. A., Fallon, C., Tricco, A. C., & Witteman, H. O. (2021). Health effects of climate change: An overview of systematic reviews. *BMJ Open*, *11*(6). https://doi.org/10.1136/bmjopen-2020-046333
22. Rolfe, S., Garnham, L., Godwin, J., Anderson, I., Seaman, P., & Donaldson, C. (2020). Housing as a social determinant of health and wellbeing: Developing an empirically-informed realist theoretical framework. *BMC Public Health*, *20*(1). https://doi.org/10.1186/s12889-020-09224-0
23. Romanello, M., Napoli, C. di, Green, C., Kennard, H., Lampard, P., Scamman, D., Walawender, M., Ali, Z., Ameli, N., Ayeb-Karlsson, S., Beggs, P. J., Belesova, K., Berrang Ford, L., Bowen, K., Cai, W., Callaghan, M., Campbell-Lendrum, D., Chambers, J., Cross, T. J., ... Costello, A. (2023). The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. In *The Lancet* (Vol. 402, Number 10419, pp. 2346–2394). Elsevier B.V. https://doi.org/10.1016/S0140-6736(23)01859-7
24. Silveira Ismael H. AND Cortes, T.. (2023). Effects of heat waves on cardiovascular and respiratory mortality in Rio de Janeiro, Brazil. *PLOS ONE*, *18*(3), 1–11. https://doi.org/10.1371/journal.pone.0283899

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- TableS1.CharacteristicsofparticipantsintheGroupModelBuildingGMBworkshopn18.docx
- TableS2.SummaryoffeedbackloopsintheCLD.docx
- TableS1.CharacteristicsofparticipantsintheGroupModelBuildingGMBworkshopn18.docx
- TableS2.SummaryoffeedbackloopsintheCLD.docx
- FigureS1.SynthesizedcausalloopdiagramCLDillustratingkeyfeedbackmechanismslinkinghousinghealthandclimateresilienceintheMinh