SPECIAL COLLECTION: LIVING LABS: AGENTS FOR CHANGE

RESEARCH

Living labs and building testing labs: enabling climate change adaptation

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ABSTRACT

Climate action requires rapid, evidence-based and locally appropriate adaptation measures. Effective responses in the built environment depend on integrated, multilevel solutions developed through inter- and transdisciplinary collaboration. Long-term, effective adaptation must fulfil five key criteria: contextual fitness, capacity for local implementation, systemic transformation, future-oriented planning and flexibility to avoid maladaptation. This study applies this analytical framework derived from climate adaptation theory to observational analyses and expert interviews to examine how building technology laboratories (BTLs) and living labs (LLs) facilitate systemic and context-specific adaptation in the built environment. By analysing purposely selected research institutions, the study conveys the potential of these laboratories to drive transformational climate change adaptation. These findings are discussed in relation to their relevance for resource-constrained regions. The cross-case study analysis of selected research facilities can inform the establishment of similar facilities in the Southern Africa region, contributing to climate adaptation research, enhancing local adaptive capacity and promoting long-term regional resilience.

POLICY RELEVANCE

In the context of a rapidly changing climate, practitioners and policymakers must act decisively to implement effective built environment-related climate adaptation measures, BTLs and LLs. Based on seven case studies, key adaptation criteria (contextual relevance, local feasibility, systemic transformation, future-oriented planning and flexibility) are used to assess how BTLs and LLs contribute to systemic and context-specific climate adaptation. Transferable lessons from these laboratories are identified and their potential application is discussed for resource-constrained settings. These insights are contextualised for Southern Africa, advocating the implementation of laboratories to enhance local research and development capacity, inform practical interventions and strengthen long-term regional resilience to climate change.

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1. INTRODUCTION

Urgent action is needed today to reduce climate change vulnerabilities. On 4 July 2023, the world recorded the hottest global average temperatures in modern history (Weather&Radar 2023); similar record-breaking temperatures were documented in 2024 (EU Copernicus Climate Change Project 2024). The world has been dealing with near 1.5°C hotter environments since May 2023 (EU Copernicus Climate Change Project 2024). Simultaneously, many regions have already crossed the critical future threshold (1.5°C) that the Paris Agreement aimed to prevent (UN 2015). As residents are living in a more dangerous world, with extreme weather conditions being normalised, climate action should no longer be considered a luxury but rather a necessity. This article considers the potential of building technology laboratories (BTLs) and living labs (LLs) to promote locally appropriate, transformational climate action.

As climate change affects multiple regions worldwide (IPCC 2022), the wide-ranging extent of these adverse climate change impacts emphasises the importance of preparing for such externalities by undertaking effective climate change adaptation strategies. Climate adaptation in the built environment requires not only technical improvements but also deeper social, policy and institutional shifts involving transformational climate change adaptation and a call for large-scale response measures to be transferred globally and tested in specific local conditions (Kates *et al.* 2012).

This study uses five criteria to evaluate the effectiveness of climate adaptation of BTLs and LLs: fitness of the solution to the local context, capacity for implementation, systemic transformation, long-term future orientation and flexibility to prevent maladaptation. Criteria such as these are widely advocated to distinguish shallow, incremental adjustments from more transformative and systemic forms of climate change adaptation (Pelling *et al.* 2015; O'Brien 2018). In this study, they function as evaluative criteria for understanding how BTLs and LLs can contribute to climate adaptation.

BTLs support contextual fitness and implementation capacity by generating and testing locally appropriate technologies (McNeil *et al.* 2014), while LLs facilitate structural transformation, long-term behavioural change and flexible real-world experimentation (Bulkeley *et al.* 2016). This article clarifies how the climate change adaptation criteria guide the analysis and how these laboratories are positioned as critical infrastructure for building adaptive capacity in vulnerable regions such as the Southern Africa region.

Africa is one of the fastest urbanising continents, with nearly 70% of its future built environment yet to be constructed by 2050 (UNEP 2022). While this expansion increases exposure to climate risks (Dodman *et al.* 2017), it also offers a significant opportunity for built-environment practitioners to shape future cities as climate-resilient urban systems. If decisive and effective climate action is taken, the rapid urbanisation of the Southern African region could shift the developmental trajectory of the region towards climate change-resilient urban environments. Achieving this, however, is challenging and requires the urgent development of locally appropriate technologies and programmes that build regional adaptive capacity (Agboola *et al.* 2023). Capacity development to guide, design and construct climate-resilient built environments is needed not only for policymakers and the public but also for built-environment professionals (Williams *et al.* 2021; De Luca 2023).

The urgent need to develop climate-resilient built environments in Southern Africa (IPCC 2022) is hampered by limited research infrastructure and networks, such as BTLs and LLs, that exist in the region (Mbatha & Musango 2022). Although Mbatha & Musango (2022) refer to the establishment of the African Network of Living Labs in 2010, few documented studies are available on BTLs and LLs in the region. Coetzee *et al.* (2012) reported similar concerns in 2012 and point out that many LLs are only planned as short-term initiatives.

Given the limited research infrastructure, coupled with rapid urbanisation and increasing climate risk, it is argued here that the opportunity exists to establish BTLs and LLs. This would advance locally appropriate climate adaptation in the Southern African region. Although distinct in structure, both approaches support the development and testing of localised technological solutions. BTLs provide controlled environments where isolated and synergistic innovations can be evaluated and refined (McNeil *et al.* 2014), while LLs, described by Bulkeley *et al.* (2016: 3) as 'forums' for co-creation, enable collaborative innovation involving professionals and end-users.

This article examines the potential of BTLs and LLs in promoting localised climate adaptation capacity and strategies. It starts by presenting an analytical framework for evaluating adaptation effectiveness in the built environment, using a logical narrative. The analytical framework is subsequently used to analyse insights from observational analyses and interviews with experts and laboratory managers of selected case studies. Using a cross-case study comparison, the study aims to establish a robust understanding of how these laboratory models can support climate adaptation in resource-constrained regions such as Southern Africa.

The article is structured as follows. Next, a literature review of BTLs and LLs is presented. This is followed by the methods and a description of the climate change adaptation evaluation criteria, before a discussion of the potential of BTLs and LLs to support locally appropriate transformational climate change adaptation.

2. BTLs AND LLs

As climate change has global repercussions, governments have started to take urgent measures at national levels to enable climate change adaptation and support climate change-resilient built environments (Biswas & Rahman 2023). Effective adaptation of the built environment requires multifaceted and multilevel strategies that provide practical, political and personal responses (O'Brien 2018). While O'Brien (2018: 155–156) supports technologically driven climate change adaptation strategies, she argues for response strategies that question the status quo and promote alternative social innovations between state and non-state actors, as well as initiatives that focus on the values and worldviews of end-users to promote behavioural changes. These climate change adaptation strategies need to be grounded in broader adaptation priorities, including enhancing the resilience of buildings, communities and ecosystems to climate-related shocks; promoting sustainable development and environmental initiatives; strengthening urban infrastructure to ensure cities remain resilient to future climate impacts; encouraging the use of innovative technologies to conserve resources; and ensuring the efficient use of natural resources through participatory community decision-making (Biswas & Rahman 2023; Ouweneel & Simpson 2023). Developing such climate change-resilient built environments requires efficient, flexible and responsive built environments that can withstand climate-induced stresses while minimising their contribution to future climate change (Hu *et al.* 2023). To inform such climate change-resilient development, it is essential to analyse existing built environments and identify opportunities for transformation (Hong *et al.* 2023).

Laboratory environments such as BTLs and LLs provide structured environments in which researchers have tested innovative adaptation strategies (Brell-Cokcan *et al.* 2023). Drawing on the experiences and insights of experts in these advanced laboratories, this study assesses the potential for similar facilities in Southern Africa to promote effective adaptations along the five key climate change adaptation criteria outlined in the introduction, and consequently discusses local capacity-building, knowledge transfer and climate adaptation solutions tailored to the region's conditions. The development and evolution of BTLs and LLs reflected a parallel shift toward sustainability, innovation and climate responsiveness in the built environment.

BTLs emerged during the Industrial Revolution (Ågren & Wing 2014), initially focusing on the strength and durability of building materials (Gooday 2008). By the late 19th century, government and university-affiliated laboratories expanded their research to construction materials and technologies, aiming to enhance sustainability, safety and efficiency (Gooday 2008). The post-Second World War construction boom in Europe further accelerated their development, with BTLs addressing energy efficiency, structural integrity and fire safety (Rosenberg 2012). The development of computers in the 1980s enabled advanced modelling and simulation for structural analysis and materials testing (Mishra & Patnayaka 2015). By the end of the 20th century, environmental concerns took precedence, prompting research on life-cycle costing, energy-efficient materials and sustainable building practices (Masseck 2017; Yilmaz & Ertekin 2023). Today, BTLs globally investigate innovative materials, systems and sustainable building compositions.

LLs gained prominence in built environment research during the 1970s and 1980s, alongside growing environmental awareness. Early projects emphasised passive solar design and natural materials, while later pilot studies in the 1980s and 1990s tested sustainable construction methods (Dabaieh *et al.* 2018). The establishment in 2006 of the 'Living Laboratory for Improving the Sustainability of Buildings' in the Netherlands marked the formal recognition of LLs, expanding research to the urban environment (Marvin *et al.* 2018). Since the 2010s, LLs have increasingly incorporated smart technologies, such as building information modelling (BIM) and the Internet of Things (IoT), to analyse climate data and enhance building adaptability. Examples include the Bullitt Center in Seattle, Washington (US), focusing on renewable energy and water conservation, and Norway's Research Centre on Zero Emission Buildings campus, testing zero energy buildings with real-time monitoring (Craddock 2021; Goia *et al.* 2015).

Building on these global insights, this study contextualises how the functions and principles of BTLs and LLs can inform adaptation strategies and capacity-building efforts in Southern Africa. In this context, BTLs improve energy efficiency and reduce material waste, while LLs accelerate sustainable innovation and foster collaboration between multiple stakeholders to integrate climate adaptation strategies (Keyson *et al.* 2017; Leal Filho *et al.* 2023). Most recent LL studies advocate large-scale adaptation planning and management (Jenewein & Hummel 2022; Smaliychuk & Latocha-Wites 2023). Both BTLs and LLs provide platforms for testing, collaboration and integration of advanced technologies in real-world contexts (Göransson *et al.* 2008).

BTLs, as specialised facilities, typically focus on the following aspects:

- *Material testing*

  Evaluating durability, energy efficiency and environmental impact, including performance under local climate conditions, to improve building stability and reduce maintenance costs.

- *Energy efficiency*

  Using simulations and experiments to assess energy-saving technologies, informing architecture and urban planning strategies.

- *Climate change adaptation*

  Developing and testing building designs that can withstand climatic stresses through physical or digital simulations.

- *Climate-responsive urban planning*

  Collaborating with urban planners to apply findings to larger urban scales.

(Trombetta & Milardi 2015)

LLs, similar to BTLs, address multiple challenges, including climate change (Lucchesi & Rutkowski 2021). Within this context, they also contribute to the following aspects:

- Establishing legislation and standards by incorporating LL findings to ensure future buildings perform under changing climate conditions (Brell-Cokcan *et al.* 2023).
- Resource management by developing and testing strategies that promote efficiency and circularity (Alamanos *et al.* 2022; Farrell *et al.* 2015; Brell-Cokcan *et al.* 2023).
- Retrofitting existing buildings to increase resilience (Brell-Cokcan *et al.* 2023).
- Developing, evaluating and refining design tools through real-time monitoring to optimise construction and design practices (Brell-Cokcan *et al.* 2023).

These BTLs and LLs provide innovative environments for addressing real-world issues, particularly climate change, through integrated research, community engagement and practical application (Afacan 2023; Song *et al.* 2021).

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3. METHODS

The experiences of researchers and managers from existing research facilities are used to assesses the potential for BTLs and LLs to strengthen local research capacity and adaptation strategies in Southern Africa. As part of a larger project focused on the development of research infrastructure to develop and test built environment-specific climate change adaptation strategies and technologies, the study employs a comparative case study analysis (Yin 2014) and assesses a purposely selected sample group using an analytical framework to examine the opportunities and challenges in utilising BTLs and LLs to promote climate adaptation and transformational climate action.

A purposive sampling approach was employed to select seven exemplary case studies across four regions, chosen based on their recognised success in the research, planning and management of BTLs and LLs. The objective was not to provide an exhaustive review of global BTLs and LLs, but to draw lessons from leading examples and expert insights to assess the potential for establishing similar laboratories in Southern Africa. This included seven case studies, two of which are located in South Africa (Figures 1 and 2).

The seven case studies include the following:

- South Africa (two sites): a BTL site managed by The Council for Scientific and Industrial Research (CSIR) in Tshwane (case study A); and the Eric Molobi site managed by the National Home Building Registration Council (case study B).
- Singapore (two sites): the Tropical Technologies Laboratory at the National University of Singapore (case study C); and SkyLab at the Building and Construction Authority (case study G).
- Sweden: HSB Living Lab, Chalmers University of Technology, Gothenburg (case study D).
- The Netherlands: Green Village, Delft University of Technology (case study E).
- US: FlexLab at Berkeley Lab, University of California (case study F).

All these facilities focus on developing sustainable technologies applicable to the built environment. Engagement with these sites comprised semi-structured interviews with expert researchers, complemented by observational analyses and visual documentation. Online interviews were conducted with experts (due to financial constraints), while on-site visits provided field-based insights to evaluate the potential of establishing similar facilities in Southern Africa.

Figure 1: Building technology laboratories (BTLs) reviewed as case studies in Singapore and South Africa.

In terms of the case study analysis, the research project followed an abductive research method (Groat & Wang 2013: 35–37). This analysis approach resulted from an inductive analysis of the case studies which identified the role of the BTLs and LLs in promoting localised climate change adaptation. Consequently, the team deductively developed an analytical framework to review and consider the efficacy of these research entities in promoting transformational climate change adaptation. This analytical framework was developed independently of the case study analysis and thereafter applied to the analysis.

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Figure 2: Building technology laboratories (BTLs) and living labs (LLs) reviewed as case studies in Sweden, the Netherlands and South Africa.

In terms of the field visits and interviews, the visits lasted between 90 and 180 min, while the online interviews lasted up to 60 min. At least one, in some cases two, senior researchers or managers of the research site were interviewed and asked to reflect on the facility they manage. Collected data were analysed thematically using observation notes, archival records and reflective diaries, consistent with established fieldwork methods (Ryan & Bernard 2003). Patterns, similarities and differences across the case studies were identified, enabling the research team to highlight current trends and opportunities in BTL and LL practices, with a particular focus on their climate adaptation potential relevant to the Southern African context.

The analytical framework used to structure the cross-case study comparison emphasises five key criteria for climate adaptation: contextual suitability, implementation capacity, systemic transformation, forward-looking considerations and flexibility to achieve resilience. Although the study was limited to seven case studies due to budgetary constraints, methodological rigour was ensured through site visits and expert consultation to achieve data saturation. Findings demonstrate how lessons from the case studies advocate for and inform the development of research facilities in vulnerable resource constrained regions.

Specific respondent identities were anonymised (only revealed where permission was granted). Draft findings were shared with consulted experts for consent and to ensure the accurate representation of their facilities.

4. CRITERIA FOR CONSIDERING THE EFFICACY OF CLIMATE CHANGE ADAPTATION

Climate change adaptation has, since its conceptualisation, been continuously redefined and applied to different contexts and scenarios to achieve specific outcomes. The focus and implementation of climate change adaptation have been significantly improved since its first mention in the Intergovernmental Panel on Climate Change's (IPCC) first assessment report (IPCC 1992). In 2014, the IPCC's fifth assessment report (IPCC 2014: 5) defined climate change adaptation as:

> the adjustment (of natural and human systems) to actual and expected climate and its effects […] to moderate or avoid harm or exploit beneficial opportunities […].

While this definition gives clear guidance to climate change adaptation strategies that need first and foremost to limit the exposure and sensitivity of inhabitants to climate change-driven risks, it also addresses multiple spheres ranging from social and economic to environmental aspects. To affect such changes, the climate change adaptation strategies must address many of these spheres (Sharpe *et al.* 2016). The latest IPCC assessment report (AR6) advocates adding equity, justice and transformation to concepts such as vulnerability and exposure when considering climate change adaptation (IPCC 2022). This raises the question of what constitutes appropriate climate change adaptation in the built environment.

Climate change adaptation strategies must be well-integrated and embedded within their immediate context to enable significant change. O'Brien (2018) argues that to impel change, climate change adaptation strategies must address three spheres: the practical (or technological problems); political systems or structures; and personal values or beliefs. To achieve such significant climate change adaptation interventions, Kates *et al.* (2012) argue that incremental interventions are insufficient and transformational climate change adaptation is needed. This study developed evaluation criteria that consider the appropriateness and efficacy of climate change adaptation strategies.

4.1 FITNESS OF THE SOLUTION TO THE CONTEXT

The fitness of the solution to the context represents one of the most critical factors in achieving meaningful climate adaptation. Adaptation measures must be closely aligned with local realities, considering the characteristics of users, the built environment, available natural resources and climatic conditions. As Smith (2010) emphasises, effective adaptation requires proactive planning that recognises local risks and long-term exposure to climate-related hazards. This involves a clear understanding of both the 'hardware' (infrastructure, technologies and materials) and 'software' (methods, maintenance and regulations) necessary to implement and sustain adaptation strategies (Jiang & Arnold 2023). Moreover, continuous monitoring and evaluation are essential to ensure these solutions remain relevant and effective over time (Mukheibir & Ziervogel 2007). Simulation modelling can further enhance this process by allowing pre-implementation assessments of potential impacts, ensuring that proposed solutions are appropriately designed for the local context.

4.2 CAPACITY TO IMPLEMENT THE SOLUTION

The capacity to implement climate adaptation solutions is a key determinant of their effectiveness. Adaptation strategies must consider not only the scale of potential hazards but also the ability of communities and individuals to respond, reducing their exposure and sensitivity to risks (O'Brien & O'Keefe 2014; Villaverde *et al.* 2024). Adaptive capacity is influenced by multiple factors, including the distribution of resources, access to knowledge, the immediate environment, existing infrastructure and human capital (Carter *et al.* 2015; Dabaieh *et al.* 2022). While households often possess some degree of adaptive capacity, broader policy frameworks and institutional support are needed to leverage this potential at community and regional levels (Lwasa 2010). Technological solutions also play a critical role: they must be accessible, understandable and adaptable to local contexts to enhance resilience effectively (Campbell 2017). Furthermore, building adaptive capacity requires both upskilling professionals for contextually appropriate design and fostering an understanding of local spatial and regulatory environments to identify the obstacles, opportunities and leverage points for climate action (De Luca 2023; Villaverde *et al.* 2024).

4.3 DEEP SYSTEMIC ADJUSTMENTS

Deep systemic adjustments are critical for meaningful climate adaptation, going beyond minor modifications to existing practices. As O'Brien (2018) highlights, addressing climate change requires identifying leverage points where substantial transformation can occur, targeting not just surface-level problems but also the root causes and drivers of vulnerability (Pelling *et al.* 2015). This includes considering deeply ingrained social norms, such as the expectations of thermal comfort and understanding the capacity of existing systems to transform (Pallubinsky *et al.*

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2023; Ziervogel *et al.* 2016). Effective deep adaptation involves multilevel planning that engages governance structures, local communities, civil society and academic institutions to identify and implement sustainable solutions (Nissanka *et al.* 2024). Such a comprehensive approach ensures that interventions address systemic social, environmental and urban vulnerabilities, ultimately fostering long-term resilience.

4.4 FUTURE-ORIENTATED LONG-TERM SOLUTIONS

Future-orientated, long-term solutions are essential for climate adaptation because adaptation measures typically involve significant initial investments and their ultimate success depends on achieving substantial long-term benefits, such as reduced vulnerability, morbidity and mortality (O'Brien & O'Keefe 2014). Planning for the future requires a thorough understanding of how interventions will perform over time under changing climatic conditions. For example, projects documented by Gething & Puckett (2013) demonstrated that modeling built projects against expected climate impacts provides insights into long-term effectiveness, enabling better cost–benefit outcomes. Similarly, De Luca (2023) and Jenewein & Hummel (2022) advocate using simulations and parametric design to create adaptive solutions capable of responding to future scenarios, while participatory approaches involving end-users help ensure that these long-term interventions remain contextually relevant and locally appropriate.

4.5 FLEXIBLE SOLUTIONS

Flexibility is a defining characteristic of societies that have successfully adapted to changing environmental and socio-economic conditions throughout history (Roaf *et al.* 2009). In the context of climate adaptation, flexibility ensures that strategies and built environment solutions remain responsive to evolving risks and uncertainties. Souza *et al.* (2015) and O'Brien & O'Keefe (2014) emphasise the importance of emergent, adaptive systems that integrate feedback loops to continuously optimise performance. Similarly, Jenewein & Hummel (2022) highlight that flexibility can be maintained through the development of adaptation pathways: incremental, iterative strategies that evolve over time as conditions change. Within the built environment, this requires an understanding of community assets and adaptive capacities, ensuring that interventions are not rigid or short-lived but capable of evolving with future climatic and contextual transformations.

5. BTLs AND LLs AS ENABLERS

In response to the urgent global climate crisis, this section explores the potential role of BTLs and LLs in enabling and accelerating climate adaptation in Southern Africa. Drawing on lessons from the case studies and insights from expert researchers involved in their management and operation, the analysis evaluates how the experience of these well-established facilities can inform the design, implementation and scaling of similar initiatives in developing regions. Based on the literature review (see Section 2), five key criteria were identified to assess the potential contribution of BTLs and LLs to local climate adaptation: fitness of the solution to the context; capacity to implement the solution; support for local implementation capacity; facilitation of long-term adaptation processes; and promotion of flexibility while limiting maladaptation.

5.1 CONTEXTUALLY FITTING SOLUTIONS

Expert respondents highlighted that BTLs and LLs play pivotal roles in ensuring the contextual fitness of adaptation solutions. According to respondents from case studies E and G, these laboratories function as vital bridges between theory and practice, translating conceptual ideas into tested, viable and market-ready innovations while simultaneously assessing their performance under different contextual conditions. A respondent from case study D further emphasised the importance of interdisciplinary collaboration within these laboratories, noting that the integration of engineering, architecture and environmental science fosters the development of holistic, multifaceted solutions. The integration of disciplines and technologies is further emphasised in a facility that focuses on resource efficiency, demand flexibility and optimisation using integrated, synergistic solutions (case study F). In these case studies, the focus shifts from conceptualising single response measures to integrated sets of response strategies where the optimisation focuses on the integration of technologies, expert interaction and context. This aligns with the broader scholarly consensus that effective climate adaptation requires interdisciplinary cooperation (du Plessis 2022; Orozco-Messana *et al.* 2020; Wright *et al.* 2021).

A persistent challenge in developing localised climate change adaptation response measures is the limited availability of data related to specific climate change impacts and the potential performance of certain climate change adaptation strategies, which hampers the design of contextually appropriate adaptation measures (Agboola *et al.* 2023). Case study G responds to the lack of data by specifically focusing on the verification and testing of technologies and their performance before introducing them to the local construction market. This allows for reliable data and research findings to inform policy decisions and building performance standards (case study G). A similar approach was followed in case study B, where the construction of test dwellings provided data regarding the implementation and performance of innovative building technologies which were then used to inform policy decision at a national level. Developing local BTLs and LLs can help overcome ill-informed policy development by generating credible datasets that support evidence-based interventions and foster research capacity at regional and national levels (Williams *et al.* 2021).

In the Southern African context, ensuring the fitness of adaptation solutions to local realities is especially critical given the region's climatic diversity, socio-economic inequalities and infrastructure gaps. Establishing regional BTLs and LLs offers practical platforms for testing and refining solutions that address these complexities. Such laboratories could help evaluate the viability of imported technologies under local conditions, promote interdisciplinary collaboration among universities and industry, and strengthen the region's capacity to generate reliable climate-related data. By supporting these efforts, Southern African climate change adaptation initiatives can move beyond theoretical adaptation planning toward applied, context-specific innovation, ultimately building a more resilient, knowledge-driven and adaptive built environment sector capable of addressing both current and future climate challenges.

5.2 IMPLEMENTATION CAPACITY AND ADOPTION OF ADAPTATION SOLUTIONS

Expert respondents emphasised that BTLs and LLs are vital for strengthening the capacity to implement adaptation solutions and their adoption by policymakers and end-users. According to respondents from case studies A, D and E, these laboratories serve as demonstration sites where alternative technologies for the built environment can be tested, refined and scaled, supporting large-scale transitions toward climate-resilient infrastructure. The respondents from case studies A and B reflected on the successes of using their research site to demonstrate technologies and showcase the viability of alternative built environment technologies and adjusting the perception of policymakers. However, they noted that this affects the functioning, layout and management of such laboratories. In contrast, case studies F and G exclude the public to ensure rigorous and reliable monitoring of the built environment, rather attributing their impact in the data generation to inform policy. While BTLs can contribute to societal transformation by promoting eco-literacy, facilitating interdisciplinary learning and encouraging paradigm shifts in education, values and professional practices (Capra 1997; Srivastava 2020; du Plessis 2022; Gillard *et al.* 2016), LLs expand this process by engaging end-users in co-design, testing and evaluation, enabling behavioural shifts and reinforcing the adoption of locally relevant solutions (case study D). While research limitations exist, such as restricted participant diversity in some LL projects (case study D), these laboratories play critical roles in establishing research and implementation networks that drive behavioural, regulatory and policy changes necessary for transformative resilience (O'Brien 2018; du Plessis 2022).

In the Southern African region, enhancing the capacity to implement climate adaptation solutions is essential given the region's complex socio-economic challenges, infrastructure gaps and climatic vulnerabilities. Establishing regional BTLs and LLs can provide hands-on platforms for testing technologies in local contexts, training professionals and engaging communities directly in co-design processes. By fostering eco-literacy, interdisciplinary collaboration and local innovation networks, these laboratories can strengthen both the technical and social dimensions of adaptive capacity. Consequently, the region would be better equipped to implement scalable, contextually appropriate climate solutions, bridging the gap between research, policy and practice to achieve lasting resilience across its built environment.

5.3 DEEP SYSTEMIC ADJUSTMENTS

Expert respondents emphasised that BTLs and LLs are essential for enabling deep systemic adjustments. LLs provide open innovation spaces where the capacity of communities and the building sector to support adaptation measures can be assessed and strengthened. These laboratories facilitate collaboration among diverse actors in the innovation ecosystem which includes innovators, integrators, testers and contributors enabling inter- and transdisciplinary problem-solving (Nyström *et al.* 2014). The importance of including diverse actors in such projects was reported by both respondents from case studies D and E. In both cases, industry partners are included in the research and development process. Case study D was initiated to include end-users in the research process. Notably, the respondents from case study D reported concerns such participant continuity, participant fatigue and limited sample group as concerns during such research projects. These experiences from LLs managers and researchers highlight both the opportunities and constraints of LLs to impel systemic changes.

While BTLs are less directly involved in co-creation, they play a crucial role in translating theoretical design solutions into physical simulations, revealing unintended consequences and potential conflicts and streamlining innovation (McNeil *et al.* 2014). Projects can also intentionally exclude end-users to ensure rigorous monitoring and factor screening (case studies F and G). Nonetheless, establishing and structuring BTLs correctly enables inter-disciplinary work which allows systemic conflicts and synergistic benefits to be identified during experimentation (case study F). Translating findings from these experiments into policy, ratings or standard changes allows for deep structural changes (case study G). While a research board is often incorporated in these BTLs and LLs (case study: D and F), the inclusion of community advisory boards allows for planned inclusion in projects where end user involvement is limited (case study A). Finally, respondents from case studies A and B noted that these demonstration sites also serve as educational platforms to disseminate research findings and technologies, supporting technological transitions while building the implementation capacity of local communities and industry.

In the Southern African context, establishing regional LLs and BTLs can provide platforms for testing, refining and implementing transformative adaptation solutions that address both systemic and social dimensions of vulnerability. By fostering collaboration across disciplines and actively engaging local communities, these laboratories can strengthen local capacity, inform policy and promote educational initiatives that enable long-term, large-scale climate resilience. Ultimately, such initiatives would help Southern Africa move from incremental adaptation measures toward transformative, context-specific interventions that reshape both societal practices and the built environment.

5.4 FUTURE-ORIENTED LONG-TERM SOLUTIONS

Expert respondents highlighted that BTLs and LLs are well-suited to support future-oriented adaptation strategies by serving as platforms for in-depth analyses and long-term scenario modelling. Respondents from case studies C and G noted that these laboratories are designed to collect and analyse large datasets, allowing researchers to evaluate the projected performance of adaptation measures over extended periods. This involved including the infrastructure and data management structures in the LLs and BTLs that were analysed (case studies D, E, F and G). These data management services are often included in the rental and utilisation contracts of the facilities (case studies D,E and G). Although digital twin technology was not explicitly implemented in the reviewed facilities, respondents recognised that integrating such approaches with physical models could further enhance their predictive capabilities (case studies C and E). By leveraging large datasets and simulation tools, BTLs and LLs enable a proactive, rather than reactive, approach to climate adaptation, ensuring that interventions are robust, scalable and capable of avoiding maladaptive outcomes (Jenewein & Hummel 2022).

Recognising the value of large, locally generated data sets can assist Southern Africa in developing future-oriented analytical capabilities, which is crucial for effective, proactive and sustainable climate adaptation strategies. Using BTLs and LLs as laboratories can enable the collection and analysis of long-term performance data, support scenario-based modelling, and integrate community and end-user perspectives into the planning process. By fostering evidence-based, locally sensitive approaches, Southern Africa can design adaptation measures that are resilient to future climatic uncertainties, reduce the risk of maladaptation and maximise the long-term effectiveness of investments in the built environment. Such future-orientated strategies are essential to building adaptive, forward-looking and resilient urban and regional systems across the region.

5.5 PROMOTION OF FLEXIBILITY

Flexibility and redundancies are important criteria to ensure climate adaptation measures are resilient solutions and do not result in maladaptation over time (Walker & Salt 2012). Continuous feedback and adjustment enables responsive solutions that can adapt to changing conditions (Jenewein & Hummel 2022).

The case studies promoted the principle of flexibility in several ways. First, several of the case studies explore transformation and retrofitting to achieve material and technological flexibility in the built environment (case studies D, E and G). Furthermore, while concepts of energy efficiency are being explored, which counters the principles of redundancies and flexibility promoted by Walker & Salt (2012), case study F actively explored energy demand flexibility to ensure energy efficiency and integrate multiple energy sources in the built environment. Finally, one LL reviewed in the study is designed to be dismantled and relocated at the end of its life-cycle (case study D), while another requires the removal of experimental installations after the research phase, demonstrating flexibility in structure articulation and material use (case study E). Both sites allow for further research and testing into integrating flexibility in the technological articulation and construction of these sites.

To manage change and ensure continuous relevance, researchers and managers emphasised the importance of continuous feedback and responsive adjustments in both research processes and physical design strategies (case studies C–E). Although most BTLs and LLs were not explicitly designed with long-term flexibility as their central goal, their operational frameworks inherently encourage experimentation and adaptation. These principles are embedded in the management of the facilities, but also through the infrastructure provision to achieve service flexibility at these sites (case study E). Such research and management practices showcase how BTLs and LLs can serve as testbeds for developing dynamic, modular and reconfigurable systems that embody the principle of adaptability (Jenewein & Hummel 2022; Walker & Salt 2012).

Embedding flexibility within adaptation strategies is essential to respond effectively to rapidly evolving climate conditions and the resource constraints in Southern Africa. Establishing BTLs and LLs that promote modular, reconfigurable and feedback-driven experimentation can ensure that adaptation solutions remain neither static nor contextually mismatched. Such laboratories would enable local researchers, practitioners and communities to co-develop and test adaptive pathways that evolve in response to shifting climatic and socio-economic realities. By prioritising flexibility, researchers and policymakers can avoid maladaptive outcomes, extend the lifespan of interventions and cultivate a built environment that continuously learns and adjusts to new challenges, therefore creating a more resilient and future-ready region.

6. DISCUSSION AND CONCLUSIONS

This discussion integrates both theoretical and empirical insights developed throughout the study. By explicitly linking observed practices, interview evidence and analytical frameworks, it provides an account of how laboratory infrastructures can facilitate transformational climate change adaptation. By reviewing building technology laboratories (BTLs) and living labs (LLs) and engaging with the experts managing and conducting research in them, the study identifies how approaches, such as applied research practices, sustainable built environment foci, transdisciplinary inclusion and contexts supporting interdisciplinary collaboration, utilised in the case studies can inform the development of similar, contextually relevant facilities in Southern Africa.

Although the selected cases represent only a fraction of the global network of BTLs and LLs, the insights drawn from these engagements highlight the potential of such laboratories to shape regional climate change adaptation pathways. Historically, BTLs and LLs have been instrumental in driving innovation in the building industry and sustainable technology development. This analysis extends this understanding by emphasising their evolving role as platforms for localised, interdisciplinary and adaptive climate action.

The findings reveal that these research entities can:

- develop contextually fitting climate adaptation solutions
- promote deep structural and behavioural change
- strengthen local implementation capacity
- support long-term and future-oriented scenario planning and
- encourage flexibility to minimise maladaptation.

While many BTLs and LLs are not always fully embedded in urban contexts, they nonetheless enable inter- and transdisciplinary collaboration, providing environments where researchers, practitioners and policymakers can co-create and test solutions in real time. Developing iterative feedback loops and collaborative testing frameworks can accelerate the transition toward climate-resilient built environments (Agboola *et al.* 2023) and the experiences shared by experts from the selected case studies support this argument.

In an era where fragmented or overly simplistic responses to climate change often fail to address systemic challenges, these laboratories offer valuable opportunities to develop integrated, locally responsive and technologically advanced solutions (du Plessis 2022; Hugo 2023; Wright *et al.* 2021). By fostering interdisciplinary research and engaging local communities in co-creation, BTLs and LLs can bridge the persistent gap between theoretical innovation and real-world implementation (Veillette *et al.* 2021).

As the global climate crisis affects all regions but manifests differently across local contexts (IPCC 2022), the capacity to generate context-specific knowledge and locally grounded data is essential to strengthening resilience in vulnerable regions. The study reveals insights from diverse laboratories in Europe, North America, Southern Africa and Asia to argue for their role in promoting transformational climate adaptation. However, the adaptation gap is significant in lower income communities and resource-constraint regions (IPCC 2022), which poses challenges to undertake climate change adaptation strategies, in this case establishing BTLs and LLs. High costs, technical requirements and operational demands associated with BTLs and LLs (Coetzee *et al.* 2012; Mukama *et al.* 2022) often limit the capacity and scalability of developing them. To address these constraints, the development of hybrid digital–physical research ecosystems is proposed to integrate digital twin technologies, shared datasets and collaborative research networks that can complement physical testing environments. Integrating advances from research facilities beyond Southern Africa and combining such innovations with physical experimentation and digital simulations can expand the scope and cost-effectiveness of climate change adaptation research in resource-constrained settings. Developing small-scale, cost-effective, physical and digital research infrastructure that is locally grounded, yet globally connected, offers an adaptation capacity development pathway for Southern Africa.

Further research should therefore focus on designing a framework for quasi-digital–physical laboratories that combine simulation-based experimentation with locally managed physical testing. Such a framework should draw from the organisational and methodological lessons of advanced laboratories while tailoring strategies to the economic and environmental realities of vulnerable regions such as Southern Africa. By fostering collaboration between international research leaders and local institutions, this approach can help leapfrog traditional barriers to development, promoting inclusive and regionally grounded innovation.

This article has demonstrated how the knowledge, methodologies and operational experience gained from advanced BTLs and LLs worldwide can be adapted to establish and sustain similar facilities in Southern Africa. This is particularly relevant to researchers and policymakers working in resource-constrained, yet vulnerable, regions. Developing such infrastructure not only strengthens local research and development capacity but also fosters long-term regional resilience through inclusive, data-driven and adaptive innovation in the built environment.

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COMPETING INTERESTS

The authors have no competing interests to declare.

ETHICAL APPROVAL

The research project obtained ethical approval to undertake the work and adhered to the stipulated ethics requirements (ethical approval number EBIT/272/2022).

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REFERENCES

Afacan, Y. (2023). Impacts of urban living lab (ULL) on learning to design inclusive, sustainable, and climate-resilient urban environments. *Land Use Policy*, 124, 106443. https://doi.org/10.1016/j.landusepol.2022.106443

Agboola, O. P., Ojobo, H., & **Aliyev, A.** (2023). Ameliorating climate change impacts on the built environment. *Civil Engineering and Architecture*, 11(3), 1324–1336. https://doi.org/10.13189/cea.2023.110317

Ågren, R., & **Wing, R. D.** (2014). Five moments in the history of industrialized buildings. *Construction Management and Economics*, 32(1–2), 7–15. https://doi.org/10.1080/01446193.2013.825374

Alamanos, A., Koundouri, P., Papadaki, L., Pliakou, T., & **Toli, E.** (2022). Water for tomorrow: A living lab on the creation of the science-policy-stakeholder interface. *Water*, 14(18), 2879. https://doi.org/10.3390/w14182879

Biswas, R. R., & **Rahman, A.** (2023). Adaptation to climate change: A study on regional climate change adaptation policy and practice framework. *Journal of Environmental Management*, 336, 117666. https://doi.org/10.1016/j.jenvman.2023.117666

Brell-Cokcan, S., Stumm, S., Kirner, L., & **Lublasser, E.** (2023). Transparency and value of data in construction: Potentials within information networks for cross-company collaboration in the production chains of the construction industry. In Trauth, D., Bergs, T., & Prinz, W. (Eds.), *The monetization of technical data: Innovations from industry and research* (pp. 539–558). Springer.

Bulkeley, H., Coenen, L., Frantzeskaki, N., Hartmann, C., Kronsell, A., Mai, L., Marvin, S., McCormick, K., van Steenbergen, F., & **Voytenko Palgan, Y.** (2016). Urban living labs: Governing urban sustainability transitions. *Current Opinion in Environmental Sustainability*, 22, 13–17. https://doi.org/10.1016/j.cosust.2017.02.003

Campbell, A. (2017). Lay designers: Grassroots innovation for appropriate change. *Design Issues*, 33(1), 30–47. https://doi.org/10.1162/DESI_a_00424

Capra, F. (1997). *The web of life: A new scientific understanding of living systems*. Anchor.

Carter, J. G., Cavan, G., Connelly, A., Guy, S., Handley, J., & **Kazmierczak, A.** (2015). Climate change and the city: Building capacity for urban adaptation. *Progress in Planning*, 95, 1–66. https://doi.org/10.1016/j.progress.2013.08.001

Coetzee, H., du Toit, I., & **Herselman, M.** (2012). Living labs in South Africa: An analysis based on five case studies. *Electronic Journal for Virtual Organizations and Networks*, 14, 1–29. http://hdl.handle.net/10204/6082

Craddock, M. E. E. (2021). Living laboratory: A circular framework for North Seattle Community College (Thesis, University of Washington). https://digital.lib.washington.edu/researchworks/items/5ab27aea-0cfd-4ca3-a10f-b29b155f5321

Dabaieh, M., El Mahdy, D., & **Maguid, D.** (2018). Living labs as a pedagogical teaching tool for green building design and construction in hot arid regions. *International Journal of Architectural Research*, 12(1), 338–355. https://doi.org/10.26687/archnet-ijar.v12i1.1285

Dabaieh, M., Maguid, D., Abodeeb, R., & **El Mahdy, D.** (2022). The practice and politics of urban climate change mitigation and adaptation efforts: The case of Cairo. *Urban Forum*, 33(1), 83–106. https://doi.org/10.1007/s12132-021-09444-6

De Luca, F. (2023). Advances in climatic form finding in architecture and urban design. *Energies*, 16(9), 3935. https://doi.org/10.3390/en16093935

Dodman, D., Leck, H., Rusca, M., & **Colenbrander, S.** (2017). African urbanisation and urbanism: Implications for risk accumulation and reduction. *International Journal of Disaster Risk Reduction*, 26(July), 7–15. https://doi.org/10.1016/j.ijdrr.2017.06.029

Du Plessis, C. (2022). The city sustainable, resilient, regenerative—A rose by any other name? In Roggema, R. (Ed.), *Design for regenerative cities and landscapes* (pp. 23–48). Springer.

EU Copernicus Climate Change Project. (2024). *Global climate highlights 2024*. https://climate.copernicus.eu/global-climate-highlights-2024#:~:text=2024%20had%20a%20global%20average,%C2%B0C%20above%20that%20level

Farrell, C., Szota, C., & **Arndt, S. K.** (2015). Urban plantings: 'Living laboratories' for climate change response. *Trends in Plant Science*, 20(10), 597–599. https://www.cell.com/trends/plant-science/abstract/S1360-1385(15)00207-1

Gething, B., & **Puckett, K.** (2013). *Design for climate change*. RIBA Publ.

Gillard, R., Gouldson, A., Paavola, J., & **Van Alstine, J.** (2016). Transformational responses to climate change: Beyond a systems perspective of social change in mitigation and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, 7(2), 251–265. https://doi.org/10.1002/wcc.384

Goia, F., Finocchiaro, L., & **Gustavsen, A.** (2015). The ZEB living laboratory at the Norwegian University of Science and Technology: A zero emission house for engineering and social science experiments. In Proceedings of PassivHus Norden Sustainable Cities and Buildings, Copenhagen, Denmark, 20–21 August 2015. https://www.researchgate.net/profile/Luca-Finochiaro/publication/282650104_The_ZEB_Living_Laboratory_at_the_Norwegian_University_of_Science_and_Technology_a_zero_emission_house_for_engineering_and_social_science_experiments/links/623d84512d8ea42c14a3cb15/The-ZEB-Living-Laboratory-at-the-Norwegian-University-of-Science-and-Technology-a-zero-emission-house-for-engineering-and-social-science-experiments.pdf

Gooday, G. (2008). Placing or replacing the laboratory in the history of science? *Isis*, 99(4), 783–795. https://www.journals.uchicago.edu/doi/full/10.1086/595772

Göransson, K., Söderlind, U., & **Zhang, W.** (2008). BTL laboratory at Mid Sweden University. In 16th European Biomass Conference, Valencia, Spain, 2–6 June 2008 (pp. 1041–1045). urn:nbn:se:miun:diva-7280

Groat, L., & **Wang, D.** (2013). *Architectural research methods*. Wiley.

Hong, T., Malik, J., Krelling, A., O'Brien, W., Sun, K., Lamberts, R., & **Wei, M.** (2023). Ten questions concerning thermal resilience of buildings and occupants for climate adaptation. *Building and Environment*, 244, 110806. https://doi.org/10.1016/j.buildenv.2023.110806

Hu, S., Zhou, X., Yan, D., Guo, F., Hong, T., & **Jiang, Y.** (2023). A systematic review of building energy sufficiency towards energy and climate targets. *Renewable and Sustainable Energy Reviews*, 181, 113316. https://doi.org/10.1016/j.rser.2023.113316

Hugo, J. (2023). Heat stress: Adaptation measures in South African informal settlements. *Buildings & Cities*, 4(1), 55–73. https://doi.org/10.5334/bc.269

IPCC. (1992). *Climate change*. Intergovernmental Panel on Climate Change (IPCC), United Nations. https://www.ipcc.ch/site/assets/uploads/2018/05/ipcc_90_92_assessments_far_full_report.pdf

IPCC. (2014). Summary for policymakers. In *Climate change 2014: Impacts, adaptation and vulnerability—Contributions of the Working Group II to the Fifth Assessment Report* (pp. 1–32). Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.1016/j.renene.2009.11.012

IPCC. (2022). *Climate change 2022. Impacts, adaptation and vulnerability. Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/

Jenewein, O., & **Hummel, M. A.** (2022). Co-creating climate adaptation pathways in coastal cities: A practical guide for engaged scholars and urban designers. *Sustainability*, 14(23), 16046. https://doi.org/10.3390/su142316046

Jiang, Y., & **Arnold, H.** (2023). Traditional water systems informing sustainable contemporary drylands design: Documentation, extraction, and deployment. *Sustainability*, 15(14), 10966. https://doi.org/10.3390/su151410966

Kates, R. W., Travis, W. R., & **Wilbanks, T. J.** (2012). Transformational adaptation when incremental adaptation to climate change are insufficient. *PNAS*, 109(19), 7156–7161. https://doi.org/10.1073/pnas.1115521109

Keyson, D. V., Morrison, G. M., Baedeker, C., & **Liedtke, C.** (2017). Living labs to accelerate innovation. In Keyson, D. V., Santin, O. G., & Lockton, D. (Eds.), *Living labs: Design and assessment of sustainable living* (pp. 55–61). Springer. https://doi.org/10.1007/978-3-319-33527-8_5

Leal Filho, W., Ozuyar, P. G., Dinis, M. A. P., Azul, A. M., Alvarez, M. G., da Silva Neiva, S., Salvia, A. L, Borsari, B., Danila, A., & **Vasconcelos, C. R.** (2023). Living labs in the context of the UN Sustainable Development Goals: State of the art. *Sustainability Science*, 18(3), 1163–1179. https://doi.org/10.1007/s11625-022-01240-w

Lucchesi, G. P., & **Rutkowski, E. W.** (2021). Living labs: Science, society, and co-creation. *Industry, Innovation and Infrastructure*, 706–715. https://doi.org/10.1007/978-3-319-95873-6_74

Lwasa, S. (2010). Adapting urban areas in Africa to climate change: The case of Kampala. *Current Opinion in Environmental Sustainability*, 2(3), 166–171. https://doi.org/10.1016/j.cosust.2010.06.009

Marvin, S., Bulkeley, H., Mai, L., McCormick, K., & **Palgan, Y. V.** (Eds.). (2018). *Urban living labs: Experimenting with city futures*. Routledge.

Masseck, T. (2017). Living labs in architecture as innovation arenas within higher education institutions. *Energy Procedia*, 115, 383–389. https://doi.org/10.1016/j.egypro.2017.05.035

Mbatha, S. P., & **Musango, J. K.** (2022). A systematic review on the application of the living lab concept and role of stakeholders in the energy sector. *Sustainability*, 14, 14009. https://doi.org/10.3390/su142114009

McNeil, A., Kohler, C., Lee, E. S., & **Salkowitz, S.** (2014). *High performance building mockup in FLEXLAB*. https://escholarship.org/uc/item/2tm2x6d3

Mishra, P. S., & **Patnayaka, R.** (2015). Simulation in architectural research. *Creative Space*, 3(1), 13–22. https://doi.org/10.15415/cs.2015.31002

Mukama, M., Musango, J.K., Smit, S., Ceshin, F., & **Petrulaityte, A.** (2022). Development of living labs to support gendered energy technology innovation in poor urban environments. *Technology in Society*, 68, 10850. https://doi.org/10.1016/j.techsoc.2021.101850

Mukheibir, P., & **Ziervogel, G.** (2007). Developing a Municipal Adaptation Plan (MAP) for climate change: The city of Cape Town. *Environment and Urbanization*, 19(1), 143–158. https://doi.org/10.1177/0956247807076912

Nissanka, S. C., Malalgoda, C. I., Amaratunga, D., & **Haigh, R.** (2024). Role of the built environment stakeholders in climate change adaptation. *International Journal of Disaster Resilience in the Built Environment*, 15(4), 649–667. https://doi.org/10.1108/IJDRBE-06-2023-0067

Nyström, A. G., Leminen, S., Westerlund, M., & **Kortelainen, M.** (2014). Actor roles and role patterns influencing innovation in living labs. *Industrial Marketing Management*, 43(3), 483–495. https://doi.org/10.1016/j.indmarman.2013.12.016

O'Brien, G., & **O'Keefe, P.** (2014). *Managing adaptation to climate risk. Beyond fragmented responses*. Routledge.

O'Brien, K. (2018). Is the 1.5°C target possible? Exploring the three spheres of transformation. *Current Opinion in Environmental Sustainability*, 31, 153–160. https://doi.org/10.1016/j.cosust.2018.04.010

Orozco-Messana, J., de la Poza-Plaza, E., & **Calabuig-Moreno, R.** (2020). Experiences in transdisciplinary education for the sustainable development of the built environment, the ISAlab workshop. *Sustainability*, 12(3), 31143. https://doi.org/10.3390/su12031143

Ouweneel, B., & **Simpson, N. P.** (2023). Securing a climate-resilient pathway for South Africa. In Hart, J. N., Harrington, C., von Lucke, F., Esteve, A., & Simpson, N. P. (Eds.), *Climate security in the Anthropocene: Exploring the approaches of United Nations Security Council member-states* (pp. 231–257). Springer.

Pallubinsky, H., Kramer, R. P., & **van Marken Lichtenbelt, W. D.** (2023). Establishing resilience in times of climate change—A perspective on humans and buildings. *Climatic Change*, 176(10). https://doi.org/10.1007/s10584-023-03614-0

Pelling, M., O'Brien, K., & **Matyas, D.** (2015). Adaptation and transformation. *Climate Change*, 133, 113–127. https://doi.org/10.1007/s10584-014-1303-0

Roaf, S., Crichton, D., & **Nicol, F.** (2009). *Adapting buildings and cities for climate change. A 21st century survival guide*. Architectural Press.

Rosenberg, F. (2012). Science for architecture: Designing architectural research in post-war Sweden. *Footprint*, 97–112. https://doi.org/10.7480/footprint.6.1-2.752

Ryan, G. W., & **Bernard, H. R.** (2003). Techniques to identify themes. *Field Methods*, 15(1), 85–109. https://doi.org/10.1177/1525822X02239569

Sharpe, B., Hodgson, A., Leicester, G., Lyon, A., & **Fazey, I.** (2016). Three horizons: A pathways practice for transformation. *Ecology and Society*, 21(2), 47. http://doi.org/10.5751/ES-08388-210247

Smaliychuk, A., & **Latocha-Wites, A.** (2023). Climate change adaptation policy and practice: Case study of the major cities in Poland. *Cities*, 141, 104474. https://doi.org/10.1016/j.cities.2023.104474

Smith, P. (2010). *Building for a changing climate. The challenge for construction, planning and energy*. Earthscan.

Song, J., Ko, Y., Hwang, J., & **Kim, C.** (2021). Exploring the feasibility of the living lab approach in addressing climate change. *International Journal of Climate Change: Impacts and Responses*, 14(1), 15. https://doi.org/10.18848/1835-7156/CGP/v14i01/15-31

Souza, K. De, Kituyi, E., Harvey, B., Leone, M., Subrammanyam, K., & **Ford, J. D.** (2015). Vulnerability to climate change in three hot spots in Africa and Asia: Key issues for policy-relevant adaptation and resilience-building research. *Regional Environmental Change*, 15(5), 747–753. https://doi.org/10.1007/s10113-015-0755-8

Srivastava, M. (2020). Cooperative learning in design studios: A pedagogy for net-positive performance. *Buildings & Cities*, 1(1), 594–609. https://doi.org/10.5334/bc.45

Trombetta, C., & **Milardi, M.** (2015). Building future lab: A great infrastructure for testing. *Energy Procedia*, 78, 657–662. https://doi.org/10.1016/j.egypro.2015.11.053

UN (2015). *Paris Agreement*. United Nations. https://doi.org/FCCC/CP/2015/L.9/Rev.1

UNEP. (2022). *2022 Global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector*. United Nations Environment Programme (UNEP). chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/ https://globalabc.org/sites/default/files/2022-11/FULL%20REPORT_2022%20Buildings-GSR_0.pdf

Veillette, D., Rouleau, J., & **Gosselin, L.** (2021). Impact of window-to-wall ratio on heating demand and thermal comfort when considering a variety of occupant behavior profiles. *Frontiers in Sustainable Cities*, 3(December), 1–16. https://doi.org/10.3389/frsc.2021.700794

Villaverde, A., Álvarez, I., Rojí, E., & **Garmendia, L.** (2024). Categorisation of urban open spaces for heat adaptation: A cluster-based approach. *Building and Environment*, 263, 111861. https://doi.org/10.1016/j.buildenv.2024.111861

Walker, B., & **Salt, D.** (2012). *Building capacity to absorb disturbance and maintain function*. Island.

Weather&Radar. (2023). *July 4 was Earth's hottest day on record*. https://www.weatherandradar.com/weather-news/july-4-was-earths-hottest-day-on-record-according-to-new-data--6367a7dd-70fe-4f16-928e-0084852b6b3a

Williams, P. A., Simpson, N. P., Totin, E., North, M. A., & **Trisos, C. H.** (2021). Feasibility assessment of climate change adaptation options across Africa: An evidence-based review. *Environmental Research Letters*, 16(7), 073004. https://doi.org/10.1088/1748-9326/ac092d

Wright, C. Y., Moore, C. E., Chersich, M., Hester, R., Schwerdtle, P. N., Mbayo, G. K., Akong, C. N., & **Butler, C. D.** (2021). A transdisciplinary approach to address climate change adaptation for human health and well-being in Africa. *International Journal of Environmental Research and Public Health*, 18(8), 4258. https://doi.org/10.3390/ijerph18084258

Yilmaz, O. C., & **Ertekin, O.** (2023). Urban living labs as a tool to achieve Sustainable Development Goal 16: A case study of Istanbul, Turkiye. *Theoretical and Empirical Researches in Urban Management*, 18(3), 88–118. https://www.ceeol.com/search/article-detail?id=1198164

Yin, R. K. (2014) *Case study research: Design and methods*. Sage.

Ziervogel, G., Cowen, A., & **Ziniades, J.** (2016). Moving from adaptive to transformative capacity: Building foundations for inclusive, thriving, and regenerative urban settlements. *Sustainability*, 8(9), 955. https://doi.org/10.3390/su8090955

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