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Reflexive co-production for urban resilience: Guiding framework and experiences from Austin, Texas

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The growing frequency and intensity of extreme weather events have placed cities at the forefront of the human, social, economic, and ecological impacts of climate change. Extreme heat, extended freeze, excessive precipitation, and/or prolong drought impacts neighborhoods disproportionately across heterogenous urban geographies. Underserved, underrepresented, and marginalized communities are more likely to bear the burden of increased exposure to adverse climate impacts while simultaneously facing power asymmetries in access to the policy and knowledge production process. Knowledge co-production is one framework that seeks to address this convergence of disproportionate climate impact exposure and disenfranchised communities. Co-production is increasingly used in sustainability and resilience research to ask questions and develop solutions with, by, and for those communities that are most impacted. By weaving research, planning, evaluation, and policy in an iterative cycle, knowledge and action can be more closely coupled. However, the practice of co-production often lacks reflexivity in ways that can transform the science and policy of urban resilience to address equity more directly. With this, we ask what kind of co-production mechanism encourage academic and non-academic partners to reflect and scrutinize their underlying assumptions, existing institutional arrangements, and practices? How can these efforts identify and acknowledge the contradictions of co-production to reduce climate impacts in vulnerable communities? This paper presents a framework for reflexive co-production and assesses three modes of co-production for urban resilience in Austin, Texas, USA. These include a multi-hazard risk mapping initiative, a resident-driven community indicator system for adaptive capacity, and a neighborhood household preparedness guide. We establish

a set of functional and transformational criteria from which to evaluate co-production and assess each initiative across the criteria. We conclude with some recommendations that can advance reflexive co-production for urban resilience.

KEYWORDS

social vulnerability and vulnerable populations, co-production and co-learning, multi hazard vulnerability, climate adaptation, urban resilience

Introduction

Research on urban resilience and urban systems has exponentially increased in recent years (Caldarice et al., 2019). This includes advancements in the fields of urban ecology (Rademacher et al., 2019), urban social-ecological systems (Crowe et al., 2016), and hazard and risk reduction (Xue et al., 2018). Global trends highlight the importance of understanding urbanization and climate change as converging issues that create multifaceted challenges that span multiple scales (Bai et al., 2017). Climate-related impacts–biodiversity loss, greenspace degradation, flooding, wildfire, extreme heat, among others – cause damage and loss to property, infrastructure, livelihoods, service provision and environmental resources. Climate change is likely to further increase the exposure in cities to climate impacts by affecting the magnitude, frequency and spatial distribution of disastrous events (Field et al., 2012; Orimoloye et al., 2019; González et al., 2021).

One promising path to mitigating climate-related hazard exposure is through knowledge co-production (Iwaniec et al., 2020; Cook et al., 2021; Amorim-Maia et al., 2022). The process of co-production is an increasingly utilized framework to generate usable knowledge by linking knowledge production and application by science, practice, and policy actors working together (Wyborn et al., 2019; Norström et al., 2020). More broadly applied, co-production is a way to produce new knowledge with a clear normative objective to support societal change (Wyborn et al., 2019). Extending a notion of reflexive governance put forth by Dryzek and Pickering (2019), we consider a "virtuous cycle" that includes three iterative phases – recognize, reflect, and response – as a positive feedback loop for urban resilience. This *reflexive co-production* can encourage actors to scrutinize and reconsider their underlying assumptions, institutional arrangements, and practices (Dryzek and Pickering, 2019; Van der Jagt et al., 2021) and move from "managing" the intersection of equity and urban resilience toward transforming community-academic-municipal government interactions. We use reflexive as a co-production adjective to emphasize a process for different actors to critically consider different ways of knowing and addressing specific problems and solutions. This is a deliberative effort to get closer to the cognitive and social patterns in the practice of science and become more attuned to the nuances and assumptions brought from the different research, policy, and community perspectives (Merton, 1987; Latour, 1991). When climate modeling, social science, lived experience, city policy and nonprofit programs integrate, a reflexive approach to co-production is warranted.

This paper focuses on a framework for reflexive co-production and assesses three modes of co-production for urban greening and climate impact risk reduction in Austin, Texas, USA. In 2013, the Austin City Council passed a resolution (#20131121-060) that directed the city manager and staff to analyze climate change projections, determine how departmental planning efforts integrate future impacts of climate change, and identify a process for performing department vulnerability assessments. Numerous efforts since then – publishing a "Climate Resilience Action Plan for City Assets and Operations" (2018), establishing "Climate Ambassadors" (2020), publishing a "Climate Equity Plan" (2021), and hiring a Chief Resilience Officer (2022) – are demonstrable efforts toward climate mitigation and adaptation in the City. Over this time period, communities in southeast Austin experienced a sequence of consequential floods (2013, 2015, and 2017) impacting many homes, lives and livelihoods. Community groups, such as Go Austin/Vamos Austin (GAVA), responded by organizing the community to increase preparedness and resilience to climate impacts through engagement, advocacy, and public accountability strategies. Concurrently, the Austin Area Sustainability Indicators (A2SI, austinindicators.org) at the LBJ School of Public Affairs at the University of Texas-Austin began focusing on climate vulnerability and community resilience (Bixler et al., 2021b; Bixler and Jones, 2022).

These (eventually) intersecting efforts create a foundation for co-production of urban resilience in Austin. This manuscript traces the interactions and processes that intertwined researchers, city agency staff, and community groups through a lens of reflexive co-production. We structure this paper as follows. First, we lay out a conceptual framework for reflexive co-production and utilize existing co-production research to think critically about the "different modes" of co-production. Specifically, we describe three co-production initiatives in Austin (Figure 1) – multi-hazard risk mapping, adaptive

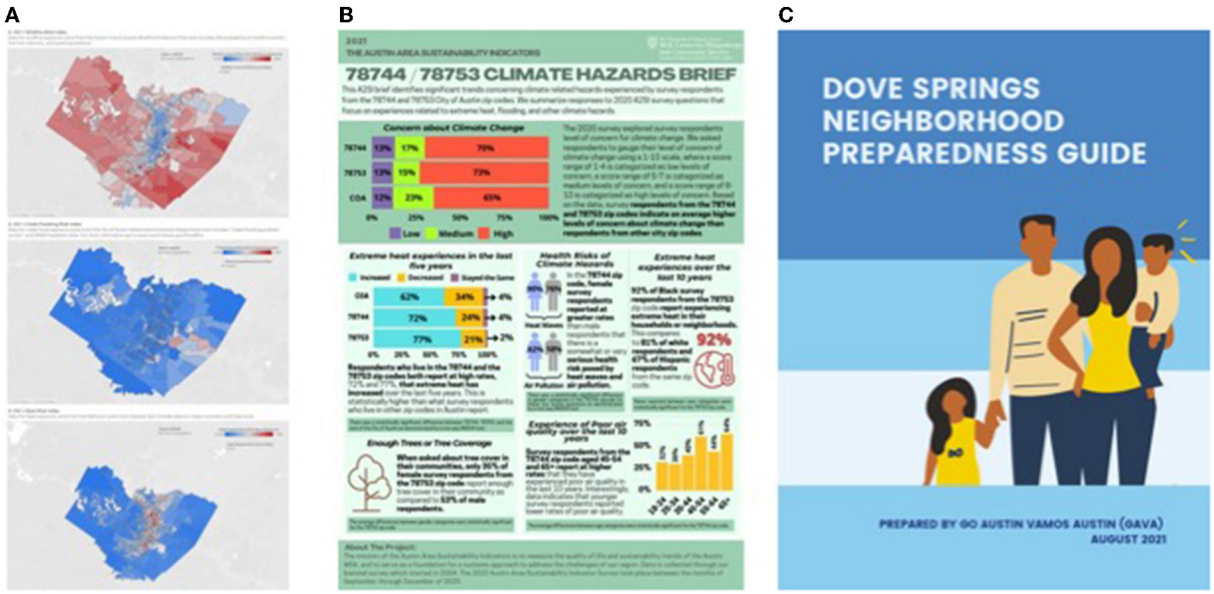

FIGURE 1
Three co-production initiatives in Austin: **(A)** multi-hazard risk mapping, **(B)** adaptive capacity indicators, and **(C)** neighborhood preparedness guide.

capacity indicators, and neighborhood preparedness plan – and examine those cases through a set of criteria distilled from recent co-production scholarship. Next, we identify some co-production contradictions, as well and highlight insights through a lens of reflexive co-production that offer practical insights for urban resilience scholarship and practice.

Study area

Austin is an economically diverse and growing city in central Texas at the edge of the Edwards Plateau and the Texas Hill Country. The 11th-largest city in the United States, Austin has an estimated population of 1,026,833 residents in 2021. The Austin Metropolitan Statistical Area (MSA), as defined by the U.S. Office of Management and Budget, includes five counties (Bastrop, Caldwell, Hays, Travis, and Williamson) and over two million people, making it the 29th largest metropolitan area in the United States. Robust population and economic growth since 2000 have increased the tax base and made Austin an attractive city for technology start-ups and established corporations alike. Major technology companies such as Facebook, Google, Apple, Tesla, Oracle, and Samsung have invested a combined >$10 billion in new manufacturing facilities and office space since 2017. Economic opportunities are matched by increasing challenges like housing unaffordability, inequitable access to services and infrastructure driven by neighborhood displacement, and increasing consumption of water and land (Richter and Bixler, 2022). This is compounded by climate projections that point to a higher intensity flood-drought regime in the region impacting human health and urban ecosystem services. Climate models show that average temperatures are increasing, the risks associated with extreme temperatures are more pronounced, and precipitation patterns are shifting, with an increase frequency in heavy precipitation and droughts (Banner et al., 2010). Historically underserved and economically marginalized communities are disproportionately impacted (Busch, 2017; Zoll, 2021).

As with many major U.S. cities, Austin's history of economic and housing segregation and broader systemic racism continues to shape the adaptation pathways and vulnerability of some neighborhoods to heat waves, drought, flooding, biodiversity loss, and wildfires. Historically marginalized communities – typically residing in a geography referred to as the "eastern crescent" of the northeast, east and southeast portions of Austin – are already stressed by limited resources, growth pressures, and higher rates of chronic disease. These social and institutional conditions define differential sensitivities and underpin disparate climate impacts across Austin's communities.

Urban resilience and co-production

Climate impacts and community resilience

Our research is situated in a literature base that is diversified, growing and evolving, and spread across many disciplines

focused on urban and community resilience (Aldrich and Meyer, 2015; Brunetta et al., 2019; Caldarice et al., 2019; Scherzer et al., 2019), adaptive capacity in relation to hazard preparedness (Pfefferbaum et al., 2013; Onuma et al., 2017; Siders, 2019; Bixler et al., 2021a), and vulnerability (Cutter et al., 2003; Adger, 2006; McDowell et al., 2016; Flanagan et al., 2018). The intersection of climate-related hazards, social vulnerability, and urban communities has become a central component of an international climate change adaptation research and policy agenda (Siders, 2019; Nalau and Verrall, 2021; Shi and Moser, 2021). Comprehensive frameworks for research and/or policy are lacking, but the common thread is clear: these areas of inquiry seek to increase community resilience by reducing climate impact exposure, decreasing sensitivity of households and communities to climate impacts, and/or increasing community adaptive capacity to mitigate the severity and intensity of climate-related disasters.

Climate extremes are increasing and intensifying loss of greenspace and biodiversity, heatwaves, droughts, wildfires and major flood events. To address this, researchers are "connecting climate extremes" (Raymond et al., 2020) through multi-risk assessments (Gallina et al., 2016) to improve understanding of disaster risk in all its dimensions (UNISDR, 2015). These concepts emphasize the increasing likelihood of climate-related compounding events, which are nonlinearly influenced by non-physical factors such as exposure and vulnerability and cut across decision-making levels from household, neighborhoods, informal and formal governance networks, and across society. Referred to as interacting, cascading, or multi-risk hazards (Pescaroli and Alexander, 2018), the framing emphasizes the interacting physical and social factors that cause their impacts to be amplified relative to the same hazard occurring separately (Raymond et al., 2020). Multi-hazard risk assessments and mapping are a tool to quantify hazard exposure and sensitivity of population to multiple climate related shocks and stressors (Adger, 2006; Pielke et al., 2021).

In addition to exposure and sensitivity, adaptive capacity is another dimension of vulnerability and urban resilience frequently considered in the literature (Pfefferbaum et al., 2013; Elrick-Barr et al., 2014; Bixler et al., 2021a; Shi and Moser, 2021; Bixler and Jones, 2022). Climate impacts are most acutely experienced at the household scale and thus increasing adaptive capacity of households is both a short-term necessity in hazard prone neighborhoods and a critical long-term hazard risk reduction strategy. Interdisciplinary frameworks and methods to measure adaptive capacity are accumulating and accelerating, but progress remains fragmented and lacking consensus (Siders, 2019). Generally speaking, attempts to operationalize adaptive capacity refer to a vector of resources and assets that can be economic, social, informational, and/or community oriented (Adger and Vincent, 2005; Norris et al., 2008; Elrick-Barr et al., 2014; Barnes et al., 2020). Adaptive capacity is a key part of the climate vulnerability equation (Adger, 2006) because increasing adaptive capacity can counteract population sensitivity and/or hazard exposure and increase community resilience.

Beyond measurement, there is an increasing emphasis and reliance on a hyper-local scale, whole community approach for effective emergency management to occur (FEMA, 2011; LaLone, 2012; Jones, 2022). Preparedness plans at the neighborhood level are one example of hyper-local scale emergency management. These plans can encourage neighborhood mapping activities, support the identification of local resources, assets, and neighborhood vulnerabilities. In theory, neighborhood preparedness plans can create opportunities for shared understanding of community risks, needs, and capabilities (FEMA, 2011) in ways that strenghten a community's resilience to climate impacts.

Co-production in a climate impact context

The thrust of community resilience and climate impact scholarship emphasize that cross-sector and interdisciplinary collaborations are critical for determining feedbacks between physical processes and societal decisions (Raymond et al., 2020) and that deep integration of knowledge bases, or convergent research, is necessary for addressing social, economic, environmental, and technical challenges of hazards (Peek et al., 2020). Co-production is a framework to address the complex nature of contemporary sustainability challenges by bringing together knowledge from academics and non-academics (Norström et al., 2020). It is a process to overcome the known barriers of knowledge use, in particular the lack of credibility, legitimacy, and relevance to decision making (Cash et al., 2003). The current concept – converged from public administration, science and technology studies, and sustainability studies – suggests that for knowledge to be actionable, the production of science should occur through scholars and stakeholders interacting to define important questions, identify relevant evidence, and co-create convincing forms of argument (Miller and Wyborn, 2020). More broadly applied, co-production is a way to produce new knowledge with a clear normative objective to support societal change (Wyborn et al., 2019). Norström et al. (2020) suggest focusing on four principles for successful co-production: context-based, pluralistic, goal-oriented, and interactive.

Urban resilience offers a somewhat unique context from which to assess the utility and impact of co-production. Earth system science that underpins climate impact research has a natural science tradition that, until recently, has had little community engagement or associated social science (Gill et al., 2021). Hazards research, particularly as it is related to climate change, can be politically polarizing and

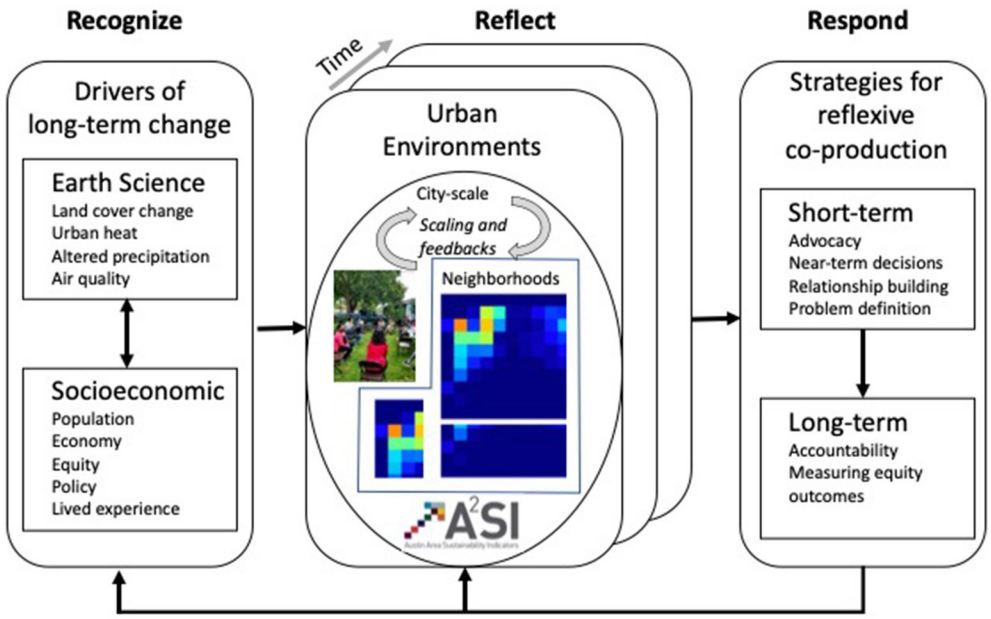

FIGURE 2
Reflexive co-production activities for Urban Resilience.

the typical emergency frames used to discuss climate-related hazards have varied political effects (Patterson et al., 2021). Challenges of modeling uncertainty, risk communication, and risk perception further complicate how scientists from different disciplines and non-scientists interact (Lejano et al., 2021), but important frameworks have been developed that help us think co-production interactions and processes in urban systems (Frantzeskaki and Kabisch, 2016; Muñoz-Erickson et al., 2017; Iwaniec et al., 2020, 2021; Cook et al., 2021;). For example, Muñoz-Erickson et al. (2017) present a framework for a knowledge systems analysis that guides description and analysis of knowledge and governance interactions in cities, and Frantzeskaki and Kabisch (2016) show how policy and science learning was linked to governance capacity in Berlin and Rotterdam. There are efforts to empirically ground existing empirical frameworks at this intersection of hazards research, risk reduction, and co-production (see Davies et al., 2015; Lejano et al., 2021), as well as a growing interest in collaborative or participatory hazard modeling (Jordan et al., 2018; Minucci et al., 2020; Sanders et al., 2020).

To many, co-production has become 'gold standard' of engaged science, though not without critique (Lemos et al., 2018). Co-production often takes time and money to develop the necessary trust to not only for together in a knowledge generating process but also to act afterwards. Important and significant questions have been raised regarding the politics of co-production and questioning if processes reinforce, rather than mitigate or transform, unequal power relations (Jagannathan et al., 2020; Turnhout et al., 2020; Chambers et al., 2021). Moreover, non-academic partners may experience partnership fatigue as scientists privilege familiarity over uncertainty of new partners or issues (Porter and Dessai, 2017). With these opportunity costs in mind, we ask what kind of co-production mechanism encourage academic and non-academic partners to reflect and scrutinize their underlying assumptions, existing institutional arrangements, and practices? How can these efforts identify and acknowledge the contradictions of co-production to reduce climate impacts in vulnerable communities?

Reflexive co-production as a guiding framework for assessing co-production efforts

We emphasize a reflexive co-production process that iterates through three phases: Recognize, Reflect, and Respond. We outline the various activities that fit within these phases in Figure 2.

We set out functional and transformational criteria for assessing co-production in urban resilience context. Functional criteria are related to process and suggest (i) value-oriented indicators that include dimensions of being (ii) context-based, (iii) pluralistic, (iv) goal-oriented, and (v) interactive (Norström et al., 2020). Context-based suggests that co-produced science should be situated within the particular social, ecological, and technical (SET) context in which they are embedded (Bixler et al., 2019b; Chang et al., 2021). Pluralistic recognizes the multiple ways of knowing, whereas goal-oriented refers to

a clearly defined and shared goals. Finally, the interactive principle acknowledges that co-production requires frequent interactions among participants throughout the process, from framing the research problem to interpreting results (Bixler et al., 2019a). Interaction throughout the process builds trust between participants, which increases the likelihood that resulting knowledge is perceived to be credible, salient, and legitimate (Cash et al., 2003). These four normative principles, if successful, lead to pragmatic, proximate, and long-term outcomes such as expanding awareness, knowledge, increasing capacity, and overcoming the barriers to knowledge utilization (Wyborn et al., 2019). This is particularly relevant and true for hazards research where significant barriers exist to effective risk communication and explicit calls have been made for increased cultural competencies among disaster risk managers (Knox, 2020; Fakhruddin et al., 2022).

Transformational criteria move beyond functional outcomes to assess how power and politics are accounted for in co-production (Turnhout et al., 2020). As a result, co-production that is transformational will establish long-term changes beyond the single intervention and empower relatively marginalized groups in the decision-making process. This moves beyond recognition and integration of local perspectives into the knowledge process and toward establishing new institutions or systems within existing institutions (Chambers et al., 2021). Transformational co-production prioritizes marginalized social concerns over technocratic solutions, explicitly integrates social equity into a climate and hazard risk reduction agenda, and changes the relationship between science, policy, and practice (Lemos et al., 2018; Wyborn et al., 2019; Turnhout et al., 2020; Chambers et al., 2021).

Applying different modes of co-production in Austin

Three urban resilience co-production initiatives in Austin

In this section, we describe three co-production initiatives applied in the City of Austin these are (i) multi-hazard risk mapping, (ii) adaptive capacity indicators, and the creation of a (iii) neighborhood preparedness plan. Ahead in "Discussion and conclusion" we will examine those cases through a set of criteria distilled from recent co-production process. We identify some co-production contradictions as well and highlight insights that can inform co-production processes in hazard risk reduction scholarship and practice. The background on the different projects is outlined in Table 1 and discussed next.

Multi-hazard mapping

The multi-hazard risk mapping project was a collaboration between academic and non-academic researchers from City of Austin agencies, as well as policy and program staff from the City of Austin (Bixler et al., 2021b). The aim of the project was to spatially map and aggregate multiple climate-related hazards – flood, heat, and wildfire – and combine those hazards with a measure of social vulnerability. The product of combining multiple types of climate impact exposure plus social vulnerability (population sensitivity) was a normalized multi-hazard risk score that City staff had for possible consideration in making resource allocation and community-engagement decisions. The activities were driven by City program staff who helped co-ordinate the data sharing between the academic research team and agency scientists.

The academic research team conducted the analysis, which included utilizing 18 variables from the U.S. Census 2013-17 American Community Survey (ACS) to construct a unique social vulnerability index (SVI) solution for Austin. Our index, although specific to the Austin area, followed established workflows and principal component analysis techniques of the established SVI (Flanagan et al., 2011, 2018) and SoVI (Cutter et al., 2003; Cutter and Finch, 2008). The exposure indices for flood and wildfire were constructed with data from the City of Austin and used established techniques in the respective fields, whereas the heat exposure score was developed using the Urban Imperviousness and Tree Canopy layers of the 2016 National Land Cover Database (Yang et al., 2018). Upon completion of the analysis, the results were discussed and verified with the City of Austin scientists and program staff and subsequently shared through the Austin sustainability indicators portal [in Figure 3 the red indicates areas with a higher composite score of exposure (to flood, heat, wildfire)] combined with social vulnerability, and available online at: https://tinyurl.com/2mme4krm.

Adaptive capacity indicators

The community indicators for adaptive capacity effort were co-developed *via* collaboration between the academic research team and Go! Austin Vamos! Austin (GAVA), a grassroots community nonprofit, GAVA organizes and mobilizes community feedback to reduce barriers to health while increasing institutional capacity to respond to the people most impacted by historic inequities. GAVA works with Austin communities to build climate resilience, among other activities such as improving nutrition, increasing physical activity, and supporting neighborhood health. This project linked GAVA strategies and actions to community indicators around resilience and adaptive capacity collected by the Austin Area Sustainability Indicators (A2SI). A biennial community survey is conducted as part of A2SI, dating back to 2004 with subsequent waves of data collection in 2006, 2008, 2010, 2015, 2018, and most recently 2020. Prior to the 2020 data collection, the research team worked with GAVA staff to co-design indicators for adaptive capacity. These indicators were informed through an iterative and pluralistic process by residents in GAVA's service area zip

TABLE 1 Summary of the three urban resilience co-production initiatives.

	Phase of reflexive co-production	Project initiated by	Collaborating partners	Funding	Co-production Activities	End-users	Products
Multi-hazard mapping	Recognize	City of Austin, Office of Sustainability	City of Austin agencies: Office of Sustainability, Watershed Protection, Austin Wildfire	None	Model conceptualization; data sharing; analytical verification; reporting design	Austin City Council; City of Austin agency staff	A spatially explicit map, interactive visualization with information at Census Block Group.
Adaptive capacity indicators	Reflect	Academic researchers	Academic researchers, GAVA	Funding to academic researchers for data collection from a philanthropic funder of GAVA	Resident's input, verification	City of Austin staff, GAVA staff and other engaged nonprofits	Creation of survey items, indicators, and measurement strategies that are resident driven.
Household preparedness guide	Respond	GAVA	Academic research team, city staff, GAVA staff	Funding from the COA to support formatting and publication of guide	Information sharing	Residents	A digital and printed preparedness guide

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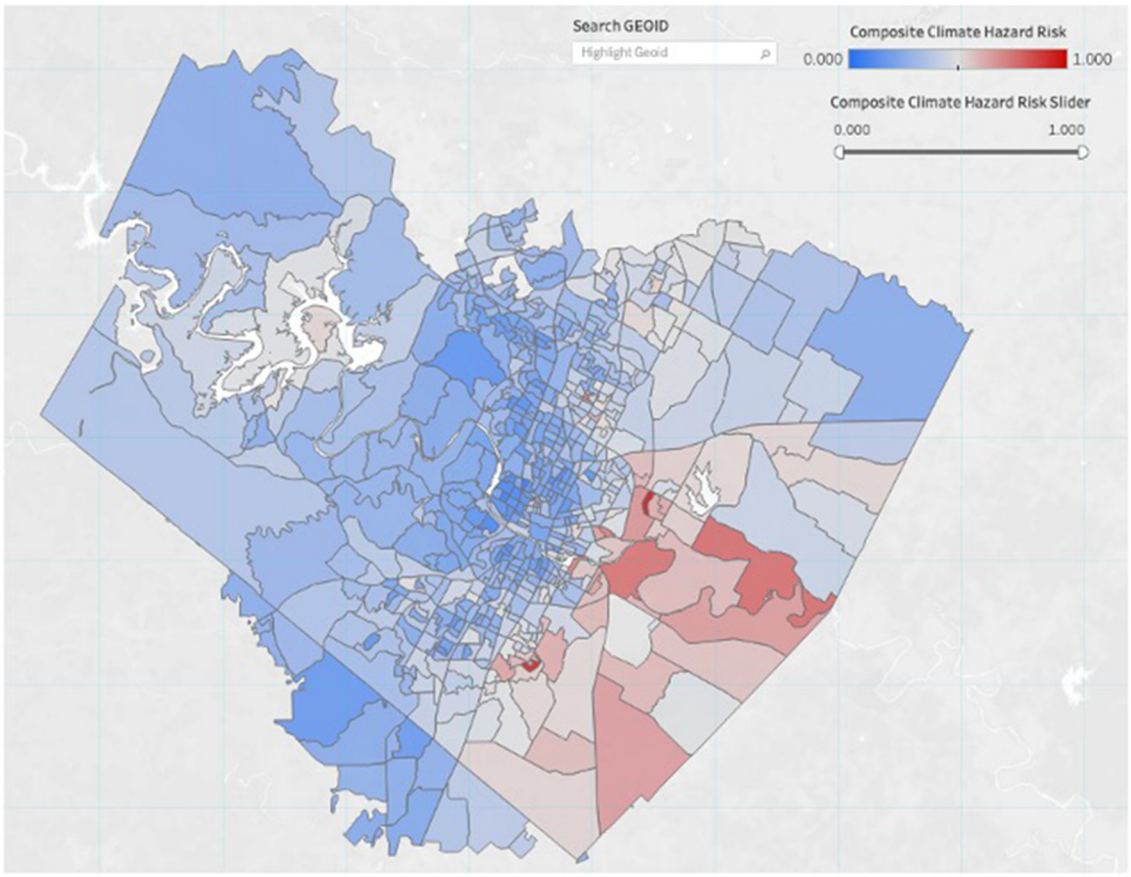

FIGURE 3
Multi-hazard risk index for Austin, Texas (for more on this see austinindicators.org and Bixler et al., 2021b).

codes: 78744 and 78753 (two historically underserved zip codes in Austin, Figure 4).

This interactive process began with the research team (1) conducting a literature review of community resilience indicators and principles. The research team presented to GAVA community organizers how to identify themes and indicators to support GAVA's mission and (2) GAVA community organizers, in collaboration with the research team, developed questions for GAVA staff to discuss with residents to identify what metrics are important to the community. GAVA community organizers then hosted 23 conversations with residents that took place in June of 2020. Notes from these conversations were translated (roughly two-thirds of the conversations occurred in Spanish) and transcribed. The research team coded the community conversations for key themes as they related to adaptive capacity and resilience, discussed those key themes with GAVA community organizers, cross-walked existing A2SI survey questions against those key themes, identified gaps, designed new and additional survey questions, and then brought the new survey items back to GAVA community organizers for review and revision. From this collaborative work, twenty-eight additional survey questions were added to the survey representing approximately 30% of the survey questions asked (not including demographic questions). In 2020, the A2SI survey data collection utilized an oversampling procedure to secure a sufficient sample size in 78744 and 78753 zip codes to reduce the margin of error in those geographies to ±5%.

Household emergency preparedness guide

Concurrently, the academic research team coordinated with GAVA and the City of Austin to develop an emergency preparedness guide, in both English and Spanish, for the Dove Springs area (zip code 78744). The Dove Springs area has been historically impacted by major flood events. The research team served a dual role in the creation of the guide. They conducted background research, where they helped identify the types of content typically found in neighborhood preparedness guides. Additionally, the research team served as project manager, where

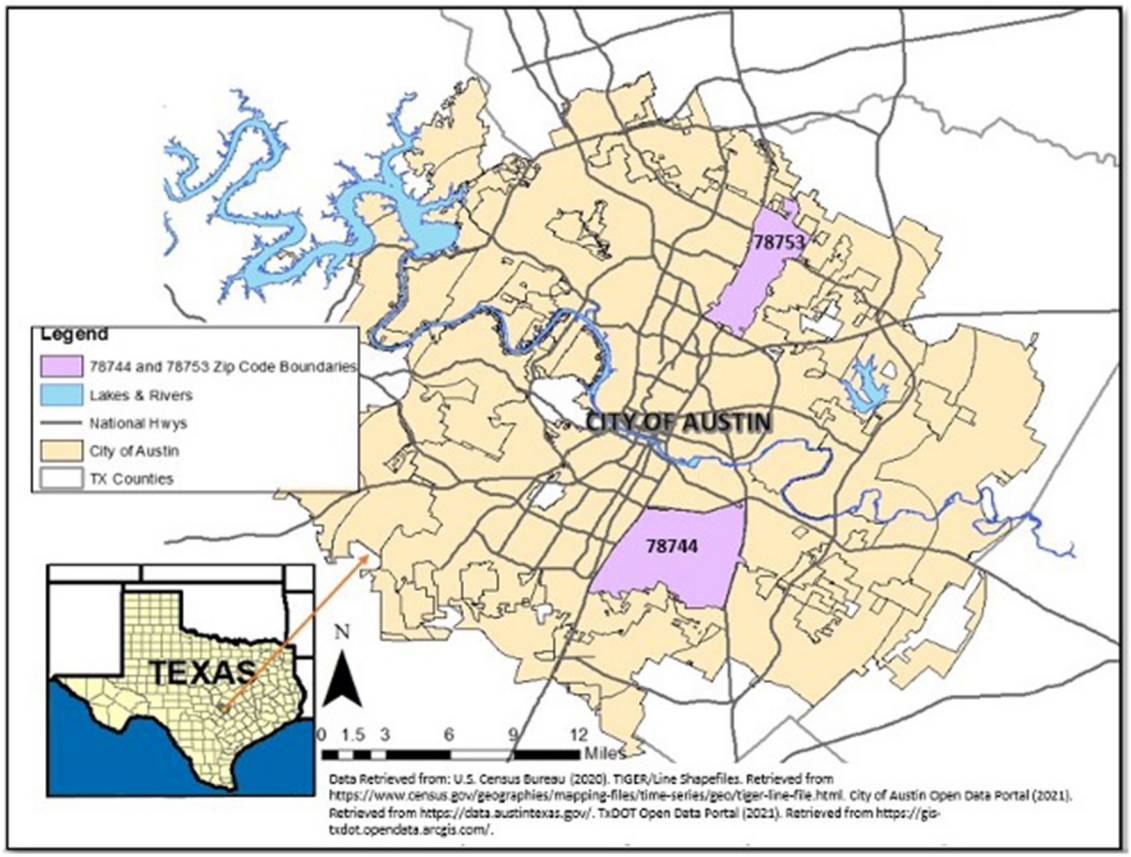

FIGURE 4
Zip codes where GAVA activities are focused and adaptive capacity indicators were developed.

they helped with the curation of the information in the guide and moving the document from draft to publication.

GAVA staff and community organizers helped identify content for the guide based on their trainings they have developed and implemented to grow a network of neighborhood "climate navigators." Working with residents and researchers they also supported the guide by ground-truthing the guide's content with residents, revised content accordingly, and revised the Spanish language version to make the guide more accessible/understandable. Meanwhile, City of Austin staff provided information about public resources available to assist in preparing for hazards and provided financial resources for publication, supported Spanish translation of the content, and helped design the guide. Although these efforts are clearly connected to the first two initiatives, how insights or information from those co-production efforts found their way into the guide was not explicit or systematic (guide available for viewing here: https://tinyurl.com/2nptmrd2). Since the creation of the Dove Springs guide, the City has used the guide as a template for a City of Austin-wide neighborhood preparedness guide.

Discussion and conclusion

The different threads of co-production started in January 2019 and are currently ongoing as of October 2022. The time period of activities was significantly impacted by the COVID-19 pandemic in terms of mediums for interaction, methods of data collection and analysis. There were also shifting priorities of both individual personnel and respective organizations as the pandemic ebbed and flowed. We organize the discussion as a linear assessment of each of the co-production criterion, while acknowledging the non-linear interaction effects of the various projects and criterion on the interactions among participants. We highlight the complexities of co-production where activities serve multiple functional outcomes and then draw some insights for urban resilience reflexive co-production.

Functional criterion

As described earlier, co-production scholarship supports the following four criteria for successful co-production: context-based, pluralistic, goal-oriented, and interactive (Wyborn et al.,

2019; Norström et al., 2020; Chambers et al., 2021; Zurba et al., 2021). We refer to these as functional criteria as they provide normative principles of what high quality and successful knowledge co-production "should be" (Norström et al., 2020). To varying degrees, all Austin initiatives intended to generate local, placed-based information, was pluralistic, goal-oriented, and interactive.

By mapping the spatial variation across the city, the multi-hazard mapping project was context-based (focused on identifying the variation of exposure and sensitivity of census block groups within a specific municipal scale) and utilized city-generated data. The project was initiated by staff from the City of Austin Office of Sustainability, who openly acknowledge that municipalities can no longer rely solely on traditional public participation processes and data from historic climatic events to determine future impacts from extreme weather. The goal-orientation of this project was clear from the start – influence policy and steer community engagement interventions being designed by City staff, GAVA and other nonprofits, as well as through course-based work at the University.

In many ways, the intended outcomes of this effort matched the achieved outcomes of this project. City staff have found the maps a useful tool in highlighting geographical areas of concern that need more investigation and the mapping outputs have been used as an object around which on-going co-production occurs. For example, the GAVA-City-University team used the quantified and visualized multi-hazard risks as a focal point for responding to a request for proposals. Multiple proposals have received federal funding (NOAA, NASA) and the team is implementing a grant-funded, GAVA-led community engagement effort in areas of high social vulnerability and high hazard risk. Financial resources from the federal grants are also going to GAVA and the community to support the engagement efforts. In this sense, the maps served as a useful boundary/research object (Lang et al., 2012) providing a platform to scaffold and co-design new research and community engagement strategies.

This project, however, was less pluralistic and interactive than it *should be*. The hazard exposure and social vulnerability modeling utilized traditional disciplinary methods. Limited input from the community was provided in shaping measurement of hazard exposure, social vulnerability, or the multi-hazard index. By contrast, other efforts at mapping social vulnerability have documented pluralistic and interactive approaches with communities (Lavoie et al., 2018; Rickless et al., 2020).

By comparison, the adaptive capacity indicators project was context-based and more pluralistic and interactive than the mapping project, however, less goal-oriented. The iterative process employed a GAVA-requested and academic team led literature review, GAVA-led interviews to identify "what is important to measure" for residents, community organization and academic team co-design of new survey items, and then circling back to the community members for review of the new survey items language. This effort was pluralistic in that representatives from the community organization (GAVA) and residents, many of whom were from predominantly Spanish speaking households, directly defined what was important to measure, thus steering the data that were collected. The intention of this process was to empower the voices of relatively marginalized actors in shaping the indicators that pointed to adaptive capacity for those who experience frequent floods and extreme heat. The resident-generated questions broadly fit within three primary themes: gentrification and resident displacement, environmental quality, and barriers/opportunities for community organizing. An example question of each of these three themes include:

- Neighbors I'm close to have been forced to move away (four-point Likert response from strongly disagree to strongly agree);
- Trees or tree cover in my community (five-point Likert from "a considerable shortage" to "more than enough")
- What are the barriers to getting organized in your neighborhood (open response)?

These and the related questions provide insight into the multiple dimensions of community resilience, broadening the scope of our previously identified and literature-based set of community indicators for adaptive capacity. Analysis of the information yielded interesting comparisons of residents of the zip codes of interest and identified strengths and gaps relative to other Austin residents. After data were collected from the 2020 A2SI survey, the research team worked with GAVA to co-design and co-develop research briefs and figures with the survey data. Once briefs were created, the information was reported back to GAVA and the City of Austin staff and interactive data sessions were conducted with community organizers and residents. Figure 5 provides an example of the data visualizations co-created and designed by the research team and GAVA, demonstrating a difference in experience of extreme heat in the specific underserved communities in relation to other zip codes in the City of Austin.

The community organization and academic team co-designed the problem frame and scope on community indicators for adaptive capacity initiative. However, the scope of resident participation was predetermined by the ongoing nature of the research and the problem framing of the project already established by the academic research team. These issues of uneven power relations have been previously identified in the literature (Turnhout et al., 2020).

In contrast to the multi-hazard mapping, the goal orientation of the adaptive capacity indicators was less well-defined. The broader framing of the project was set to establish baseline measurements as part of an ongoing, biennial, effort to track a broad range of sustainability and community resilience

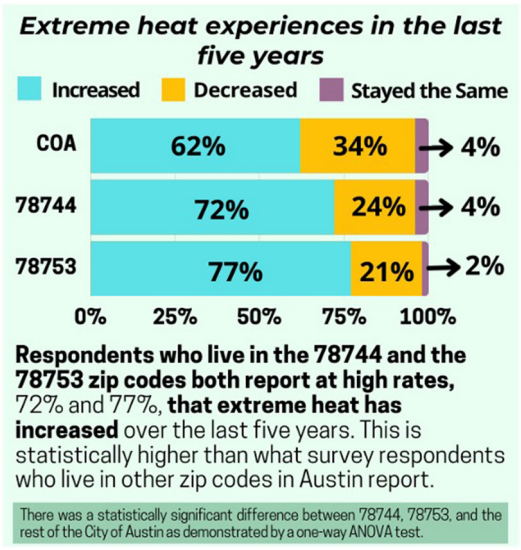

FIGURE 5
Example of resident derived adaptive capacity indicators.

indicators in the service area zip codes and across the city. The research team struggled to identify how to best represent the data as visualizations and how and when to test for statistical significance (and if it was important in this context). Additionally, making a direct connection between utilizing the survey data for program and organizing strategies has been challenging to implement.

Weaving components of both projects was the effort to develop a neighborhood preparedness guide. The resident hazard preparedness guide is context-specific information tailored for residents of one specific zip code – 78744 – that experiences frequent and intense flooding and extreme heat events. The effort was coordinated by the academic research team yet was pluralistic in that it compiled the most up-to-date resources from the city and cross-referenced with residents the knowledge needs as articulated by the residents. This effort was extremely context-based and goal-oriented. From project initiation to completion, the project aim was developing a resident-centered guide that GAVA could utilize in public information and training workshops that are conducted in that specific neighborhood. Since published, the guide has been distributed to residents through GAVA's climate navigator program. In 2022, the research team, GAVA, and the City of Austin collaborated to create a city-wide neighborhood guide.

Transformational criterion

A meta-analysis of co-production identified two distinct ways that co-production efforts engage with politics: empowering relatively marginalized groups or by influencing powerful actors (Chambers et al., 2021). The multi-hazard mapping project provided municipal officials science-based evidence to inform decision-making. Improved and refined technical modeling of hazards is of little use if not embedded in the policy, regulatory, institutional, and cultural factors in which hazard mitigation and preparedness occurs. Implicitly, the effort sought political engagement, with the intentions to highlight the unequitable distribution of hazards among historically marginalized neighborhoods in the city. The report was acknowledged by the Austin City Council and has shaped decisions and strategies at various municipal department levels. The initiative was an effort to reframe the solution set: city leadership and staff were challenged to move from resilience planning of municipal assets to communities made up of households with residents. This project generated a method and evidence to understand social vulnerability and the spatial relationship to various climate-related hazards.

The maps – the social vulnerability map in particular – highlighted the legacy of racial and economic disparities between east and west Austin institutionalized through racial segregation in the 1928 City Master Plan. Many of the once racially segregated neighborhoods are identified as "hot spots" for climate-related risk identified in the multi-hazard mapping, providing evidence and justification for ongoing City-led community engagement and climate adaptation efforts, a response to previous efforts being "color-blind" (Zoll, 2021).

The contradictions of the functional criteria, however, also created barriers for transformational policy and engagement. The information generated from the multi-hazard mapping project is "context-based" at the municipal level, yet too coarse for understanding street or household level variation within neighborhoods. The decision to map at the scale of the census block group was driven solely on the methodological considerations of census data availability used for the social vulnerability index. Social vulnerability and flood exposure may vary significantly within a census block group and our current approach, which accounts for geographical variation at one scale, does a poor job at finer scales. This has been a point of critique from the community organizations when conversations extend beyond researchers and city program staff. To this end, the project engaged with top decision-makers and advanced existing policy goals, although has not yet shifted institutional or management practices. This initiative did little to directly empower relatively marginalized actors, articulate, or mobilize the voices, knowledge or perceptions of different participants or address institutions of decision-making or governance.

The adaptive capacity indicators, in contrast, sought to integrate resident perspectives into the indicator design process and empower relatively marginalized voices to create more meaningful representations of what is important to measure and track. This effort sought to increase the knowledge base and issue awareness of resident-defined

metrics, thus creating opportunities for those most affected to redefine the range of climate adaptation solutions to include anti-displacement/gentrification, opportunities for political engagement, and broader environmental quality. That said, there was little space created to redefine the process and/or transform the broader system of governance, knowledge production processes, or strategies for delivering hazard mitigating related services. Moreover, the community indicators for adaptive capacity effort present another functional co-production contradiction. On the one hand, this initiative empowers resident voices to shape what outcomes are important and what should be measured and reported, yet the data collection and analysis of indicators treats the residents and resident information as the object of research through deductive data collection, analysis, and reporting. Other relativistic and/or systems thinking designs could bring resident voices closer to academic and city staff for more direct conversations, and transformations, of systemic governance issues.

The neighborhood preparedness guide brought City staff, community organization staff, academic researchers together to generate and compile information for residents. To date, there is little evidence this has shifted the strategies or priorities of decision-makers or led to changes in resident preparedness. There are plans for the guide to be a focal point in community workshops led by GAVA as part of their "climate navigator" efforts to increase neighborhood preparedness capacity. Similar to the hazard maps, this guide has the potential to serve as a boundary object for creating safe spaces to identify the governance barriers and opportunities for better climate preparedness at hyper-local scales.

Conclusion

The three initiatives discussed were constituted by overlapping set of actors (academic, community, city partners) across the same period. The various threads of interaction have been necessary to build trust between the participants and provided opportunities to continue various co-production processes beyond the delivery of the final products from the projects reported here. Interestingly, early co-production scholarship focused on service delivery (Brudney and England, 1983), however the recent renaissance in science and technology and sustainability studies has significantly focused on knowledge creation and utilization. We find that functional and transformational co-production in a hazards context generates knowledge, reduces barriers to knowledge utilization in designing solutions or services, but importantly also should involve the co-production of public goods service delivery. This is the "respond" phase of the reflexive co-production cycle and points toward the iterative virtuous cycle of building urban resilience.

There are multiple pathways through which reflexively responding can occur: reducing hazard exposure, reducing population sensitivity, and/or increasing adaptive capacity (Adger, 2006). In all cases, functional and transformational co-production needs to account for the mix of services and products as part of the output of co-production (Alford, 2014). What green or gray infrastructure services reduce exposure to hazards? What social services reduce population sensitivity? What program interventions increase adaptive capacity? These are future studies that currently underway by the academic, city staff, and community organization team. In all cases, municipal and community organization partners design and deliver climate services with the intended outcome to increase community resilience. Reflexive co-production, when applied to urban resilience initiatives, can more explicitly connect knowledge and service co-production through the recognize, reflect, and respond cycle.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RB contributed to writing, analysis, and research design. SR contributed to writing. MC contributed to writing, different initiatives, and work on the ground. JJ contributed to different initiatives and engagement with GAVA. NA and CL contributed to different initiatives and work on the ground. MB contributed to initiatives and community engagement. PP and DN contributed to research design and funding acquisition. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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