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The Co-Production of Sustainable Future Scenarios

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ABSTRACT

Scenarios are a tool to develop plausible, coherent visions about the future and to foster anticipatory knowledge. We present the Sustainable Future Scenarios (SFS) framework and demonstrate its application through the Central Arizona-Phoenix Long-term Ecological Research (CAP LTER) urban site. The SFS approach emphasizes the co-development of positive and long-term alternative future visions. Through a collaboration of practitioner and academic stakeholders, this research integrates participatory scenario development, modeling, and qualitative scenario assessments. The SFS engagement process creates space to question the limits of what is normally considered possible, desirable, or inevitable in the face of future challenges. Comparative analyses among the future scenarios demonstrate trade-offs among regional and microscale temperature, water use, land-use change, and co-developed resilience and sustainability indices. SFS incorporate diverse perspectives in co-producing positive future visions, thereby expanding traditional future projections. The iterative, interactive process also creates opportunities to bridge science and policy by building anticipatory and systems-based decision-making and research capacity for long-term sustainability planning.

1. Introduction

Urban sustainability challenges require anticipatory planning to address future uncertainty. Multiple and compounding social, ecological, and technological stressors—such as growing inequality, extreme climatic events, and aging infrastructure—test the resilience of urban systems. Given the complexity and growing magnitude of stressors, cities are moving from predict-and-prevent approaches that respond to well-defined risks to resilience- and sustainability-building approaches that consider a range of potential shocks and pressures (Measham et al., 2011; Romero-Lankao, Gnatz, Wilhelmi, & Hayden, 2016; Tyler & Moench, 2012). Furthermore, these approaches introduce normative elements and systems thinking that integrates diverse perspectives. To scope future resilience and how to achieve it, it is essential to consider both the dominant future priorities of a city and the marginal future visions in that city (Pelling, 2010; Vogel, Moser, Kasperson, & Dabelko, 2007). In this context, scenario development presents an important tool to help cities anticipate, adapt, and transform.

Scenarios are plausible, coherent narratives about the future of a place or a situation for the production of anticipatory knowledge (Millennium Ecosystem Assessment, 2005). In recent decades, scenarios have been used in sustainability science to guide scientific inquiry, integrate diverse data and knowledge, and compare alternative policies. Scenario development has taken both forecasting approaches—looking to the future based on past, existing, and anticipated conditions—and backcasting approaches, which start from a desired future condition and determine what it would take to achieve the end goal (Iwaniec, Childers, VanLehn, & Wiek, 2014). More recently, sustainability

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scenarios incorporate positive futures, systems thinking, and a transdisciplinary approach that prioritizes scenario development in participatory settings (Raudsepp-Hearne et al., 2019; Pereira, Hichert, Hamann, Preiser, & Biggs, 2018; Bennett et al., 2016; McPhearson, Iwaniec, & Bai, 2016; Iwaniec et al., 2014; Nassauer & Corry, 2004).

In contrast to the dominant discourse of dystopian futures, scenarios characterized by desired outcomes create visionary and innovative opportunities (e.g., Gaziulusoy & Öztekin, 2019; Bennett et al., 2016; McPhearson et al., 2016; Nassauer & Corry, 2004). A systems approach to urban sustainability scenarios asks practitioners and researchers to consider the interactions, potential tradeoffs, and synergies among goals, instead of squarely focusing on a particular outcome (Carpenter, Booth, & Gillon, 2015; Iwaniec & Wiek, 2014; Iwaniec, Cook, Davidson, Berbés-Blázquez, & Grimm, in review). In order to incorporate diverse perspectives and visions, scenarios may be developed in transdisciplinary and participatory settings that range from consultation to co-production (Jahn, Bergmann, & Keil, 2012; Lang et al., 2012).

In this paper, we present the Sustainable Futures Scenarios (SFS) framework (Fig. 1). The SFS framework offers guidance to co-produce visions and transition pathways of positive futures that develop and integrate interventions for sustainability transformations of social-ecological-technological systems. The SFS framework offers an approach for comparing distinct normative scenarios and exploring alternative policies and their long-term implications. The scenarios co-produced through the SFS framework richly describe future social-ecological-technological systems (SETS). In other words, the scenarios integrate visions of the future social-cultural-governance system with the ecological-biophysical system and the technological-engineered-infrastructure system in the city. With positive SETS future visions, researchers and practitioners can explore transition pathways to achieve the sustainability and resilience goals that have been negotiated in the co-production setting. Normative values ascribed as "positive" futures are negotiated by participants in the co-production setting.

This approach has been applied in the Central Arizona-Phoenix Long-term Ecological Research site (CAP LTER) and the nine study cities of the Urban Resilience to Extreme Events Sustainability Research Network (UREx SRN). In this paper, we demonstrate the application of the SFS framework with the positive urban futures that were co-developed for the CAP LTER metropolitan region. The goal of this initiative was to open up the solution space to explore robust future pathways. The case study allows us to demonstrate how the framework can be used to (a) adopt iterative engagement with stakeholders; (b) develop research and decision-making capacity for long-range planning; (c) address urban resilience and sustainability challenges.

2. Sustainable future scenarios

2.1. Framework

The SFS framework incorporates three distinct scenario logics: strategic, adaptive, and transformative scenarios (Fig. 1). The three scenario logics vary in the production approach and resulting visions. The strategic scenarios are aligned with forecasting approaches that explore the question, "what if the goals and strategies articulated in governance and city planning documents were implemented (Iwaniec et al., in review)?" Given the nature of these documents, strategic scenarios reflect the city's formal aspirations for short- (≤5 years) and mid-term (≤20 years) horizons extended into the long-term future (e.g., to the year 2060 or 2100). Because strategic scenarios are closely related to ongoing initiatives and the current, dominant planning paradigm, they serve as an effective baseline comparison to the co-developed positive visions of the city. The adaptive scenarios are co-developed in a participatory setting and explore interventions to address specific challenges, such as those posed by persistent problems, emergent challenges, or extreme events. Adaptive scenarios rely on the intermix of forecasting and backcasting approaches ("bi-directional" vantage point; Crawford, 2019). Predictive forecasting (through both quantitative modeling and expert judgement) informs the co-production process to clearly describe the problem being addressed and to iteratively evaluate and revise the scenario to inform backcasted outcomes of the resolved challenges (Robinson, Burch, Talwar, O'Shea, & Walsh, 2011). Finally, the transformative scenarios are co-developed to explore normative, radical departures from the status quo that transform the city's current social, ecological, and technological systems. Transformative scenarios apply backcasting approaches by starting from sustainability visioning (Wiek & Iwaniec, 2014), followed by the development of transition pathways from the envisioned future state to the current state (horizon mission methodology (see Bishop, Hines, & Collins, 2007); modified to accommodate the co-production process).

While all three logics are intended to explore positive futures, they are situated along a plausibility-desirability continuum (Fig. 1). Plausibility comes from the explicit link to the existing context that shapes how the future could look. On the other hand, a focus on desirability integrates normative perspectives and places emphasis on what the future ought to look like. However, adaptive scenarios may include transformative elements that are highly desirable, and transformative scenarios may include highly plausible features.

At the outset, participants may have difficulty engaging in transformative thinking that radically departs from the status quo and

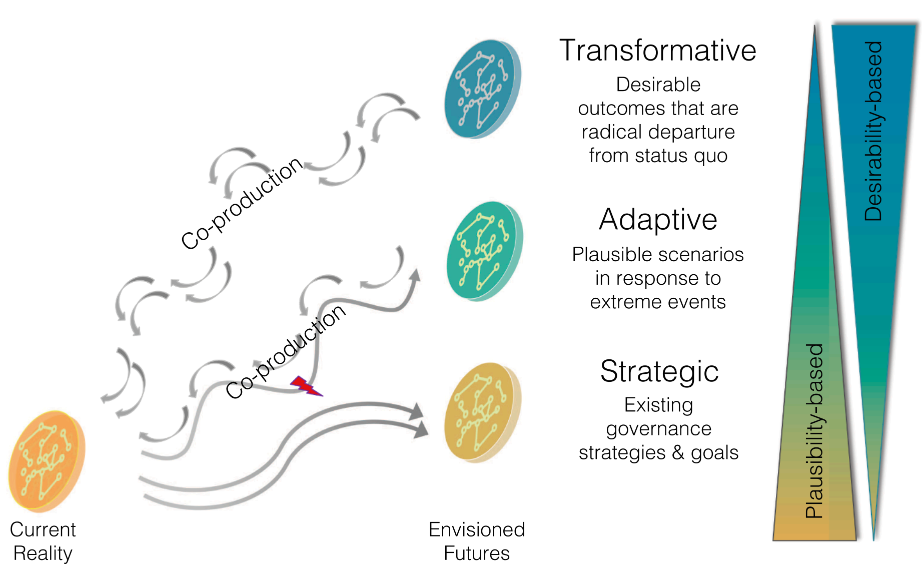

Fig. 1. The Sustainable Futures Scenarios (SFS) framework comparing strategic, adaptive, and transformative scenarios on a plausibility-desirability continuum and the diverse approaches in scenario development. Gray arrows represent transition pathways from current reality to achieve the future scenario. In the strategic scenario, the transition pathway is projected forward from the current state; in the transformative scenario, the transition pathway is backcasted based on future goals; in the adaptive scenario, the pathway is developed from a combination of projections and backcasting. Red glyph indicates potential disturbance(s) (e.g., an extreme event) that the adaptive scenario addresses along the transition pathway. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

challenge existing, dominant systems (Pereira, Sitas, Ravera, Jimenez-Aceituno, & Merrie, 2019). The strategic, adaptive, and transformative scenario approaches help build anticipatory capacity and allow for critical thinking on transformative change. Strategic scenarios acknowledge previous planning efforts, and are used to explore if the existing goals are sufficient to address the city's pressing issues. Adaptive scenarios then focus on unresolved challenges: through an exploration of vulnerabilities and uncertainties, participants develop social-ecological-technological innovations to address them. The ability to think critically about transformative change is enhanced by providing opportunities for participants to: explore long-term implications of existing planning goals; build an understanding of the suite of vulnerabilities and uncertainties faced; and develop solutions to address their most pressing challenges and even those that might arise in the future (i.e., unknown unknowns). This creates the space for the exploration of scenarios of transformative change that probe the limits of what is normally considered possible, desirable, or inevitable.

2.2. General approach

The SFS process is structured as co-production workshops organized into phases (Fig. 2). We start with scoping and framing (phase I) to identify collaborators, key challenges and goals, spatial and temporal scales, and scope of the scenarios. Next, we define scenario logics (phase II) and draft preliminary representations of diverse futures. Third, to increase scenario specificity (phase III), we iteratively specify details of the myriad metrics, targets, strategies, and pathways. We conclude with scenario exploration (phase IV) through modeling and qualitative assessment of the scenarios to further explore and revise the sustainability scenarios. The SFS process is a sequence of iterative and reflexive procedures, following quality criteria (visionary, sustainable, systemic, coherent, plausible, tangible, relevant, nuanced, motivational, and shared; Wiek & Iwaniec, 2014) as design and evaluation guidelines for sustainability visioning. In the descriptions of each phase, we note the emphasis on specific quality criteria.

2.3. Phase I: Scoping & framing

The SFS approach ensures relevance to the local context by exploring the city's goals and challenges for the future. The first phase of the scenario development process identifies the relevant: (a) spatial and institutional boundaries (e.g., neighborhood, municipal, or metropolitan), (b) future time frame (e.g., for the year 2060 or 2100), and (c) the participatory setting, including who will be involved in the different roles. Potential partnerships may be identified from stakeholder mapping, content analyses of governance documents, and formal and informal interviews with diverse and representative stakeholders (Iwaniec et al., in review). These sources also reveal who is most affected, most influential, or most underrepresented in decision-making about the future. Likewise, interviews and content analysis of local governance documents, such as development, resilience, and sustainability plans, can be useful to understand the existing goals and challenges. The Scoping & Framing phase is designed to identify the needs and current context of the system; however, it may be revised in the future by the practitioner-researcher team. Another key outcome of the Scoping & Framing phase (and subsequent phases) is to develop shared understanding and buy-in among the practitioners and researchers (quality criteria: shared and motivational).

2.4. Phase II: Defining scenarios

Following the Scoping & Framing in phase I, workshop participants deliberate scenario themes in phase II. To begin, scenario themes are articulated as broad aspirational goals or persistent and emergent challenges that the team would like to explore. Activities in this phase—such as discussing extant and emergent vulnerabilities, eliciting vision statements, identifying megatrends and weak signals, and conducting systems mapping—allow for rapid prototyping and brainstorming (Iwaniec et al., 2014). Using both forecasting (e.g., from existing and anticipated challenges for adaptive scenarios) and backcasting (e.g., from vision elements for transformative scenarios) techniques allows different entry points for exploring the themes and future pathways to positive futures. From the diverse pool of scenarios, the practitioner-researcher team comes to a consensus on key scenario themes, goals, and challenges to explore and refine further. An outcome of this phase is the development of distinct future visions with clear goals or challenges that each scenario will address. Through participatory deliberation, this phase develops normative and future-oriented capacities of stakeholders (quality criteria: visionary and relevant).

2.5. Phase III: Scenario specificity

The third phase focuses on developing the transition pathways from the goals (transformative scenarios) or that address the challenges (adaptive scenarios) identified in phase II. Participants first identify strategies—the social-ecological-technological interventions—needed to achieve each goal or address each challenge. Activities are designed to add details to the scenario, including: 1) defining targets, indicators, and metrics of the strategies and systems linkages among the strategies; 2) participatory spatial mapping of key locations that identify where

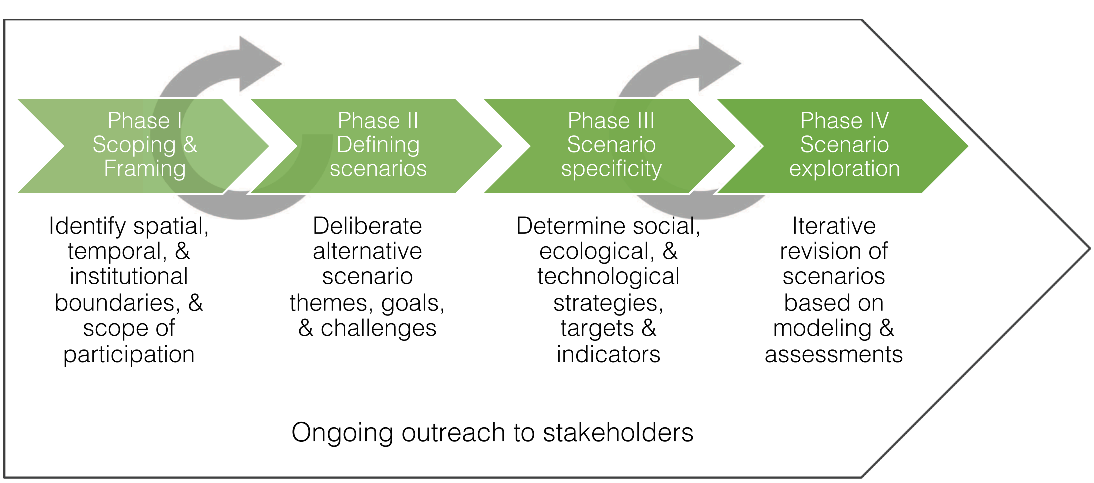

Fig. 2. The four phases of the iterative process used in creating positive future vision are: (I) Scoping and framing, (II) Defining scenario logics; (III) Identifying specific strategies; and (IV) Exploring and refining scenarios. All phases are performed in facilitated collaboration with relevant stakeholders.

and for whom particular strategies will be implemented; 3) sequencing transition steps on a timeline to achieve each goal; 4) identifying key actors and institutions responsible for implementing each strategy; and 5) developing actor-oriented narratives and place-based design vignettes to richly describe and make the scenarios tangible. A key outcome is to provide enough spatial, temporal, and other key details to clearly articulate the scenario visions, delineate the transition pathways, and parameterize subsequent scenario explorations. This suite of activities ensures that scenarios are richly described (quality criteria: systemic, coherent, tangible, relevant, and nuanced).

2.6. Phase IV: Scenario exploration

The scenarios can be evaluated through quantitative modeling and qualitative sustainability and resilience assessments to compare potential implications and tradeoffs of alternative visions. Through exploration of the diverse modeling and assessments outcomes, the scenarios can be refined to better reflect desired outcomes. As an example, the land use/land cover changes that result from envisioned zoning policies can serve as inputs to process-based models that simulate hydrologic flow paths. If the envisioned land configuration does not produce the desired change (e.g., reduced flooding) or introduces unintended consequences (e.g., exposure to flooding in an area that was previously protected), the participants may choose to adjust zoning strategies to reduce the projected impact. This final phase iteratively evaluates, revises, and refines the scenarios (quality criteria: sustainable, plausible).

2.7. Iterative nature of phases I–IV

Dissemination entails more than just meaningfully conveying the final visions and pathways and is therefore interspersed throughout the process. Dissemination engages a broader community to review and validate the visions, develop opportunities for further engagement, and ensure transparency. Co-development of the dissemination plan facilitates buy-in and accountability. Art, designs, games, narratives, and action-oriented activities are key in making the scenarios tangible and sparking implementation of the visions.

The multi-phase approach encourages divergent, creative thinking by eliciting diverse perspectives (phases II and III) as well as convergence through negotiation and consensus building (phases III and IV). While the phases may be conducted sequentially, they are designed to iteratively respond to emerging needs throughout the SFS process.

3. Case study

3.1. Central Arizona-Phoenix

The Central Arizona-Phoenix (CAP) region is the site of a Long-Term Ecological Research (LTER) project (Grimm et al., 2013), which provided both the impetus and much of the background data for the SFS project. The CAP LTER study region comprises an expansive urban ecosystem and surrounding agricultural and protected lands in the semi-arid northern Sonoran Desert of south-central Arizona, USA. Within the CAP LTER study region, the greater Phoenix metropolitan area is home to over 4 million people living in more than 20 municipalities (U.S. Census Bureau, 2017). The CAP LTER region is expected to face increasingly extreme droughts, heat events, and flooding due to changing climate and precipitation patterns (Garfin, Jardine, Merideth, Black, & LeRoy, 2013). The region also faces current and future challenges due to a growing population and a prolonged (19 year) drought (Georgescu, Moustaoui, Mahalov, & Dudhia, 2012). Surface water supplies and storage are in jeopardy.

The central goal of the CAP SFS initiative was to address long-term challenges of the region by exploring positive future pathways and developing transdisciplinary research and decision-making capacity. Through a collaborative process with practitioners and researchers, we developed seven normative scenarios (1 strategic scenario, 3 co-developed adaptive scenarios, and 3 co-developed transformative scenarios) for the years 2015–2060.

3.2. CAP SFS case study: application and methods

For phase I, we conducted a survey and held meetings with practitioner and academic stakeholders in August through December 2014. The meetings were one-on-one conversations and small group dialogues (< 30 participants) from which a list of workshop participants was developed through snowball sampling. We also determined the spatial boundaries, temporal scope, and the initial framing for the adaptive scenario themes (extreme drought, flooding, and heat).

To develop the strategic scenario, we conducted a content analysis of 23 governance and visioning documents from five municipalities in the CAP LTER region. Through the content analysis, we identified key goals, quantitative and qualitative targets associated with the goals, and intervention strategies (see Iwaniec et al., in review for further details on developing a strategic scenario). While the strategic scenario was not co-produced within the SFS participatory workshops, it was validated in the evaluation phase.

In phases II–IV, scenarios were developed as a series of six full-day workshops held between December 2014 and January 2017. These workshops were attended by a diverse group of community leaders, decision makers, planners, and academics. The stakeholders represented federal, tribal, state, county, and city agencies, as well as non-governmental organizations and universities (see https://sustainablefutures.asu.edu/about/ for names of participating institutions that agreed to be listed). Each workshop consisted of presentations and discussions in plenary to frame the day's objectives, followed by alternating small-group and plenary activities. Small groups were composed of practitioners and researchers as participants in the co-production setting. The facilitated small groups focused on the co-production of tasks for each of the activities described below. Each small group generally focused on activities to develop a single scenario at a time (except during comparative and assessment activities in later workshops). However, the participants of the small groups were shuffled during the workshops to diversify perspectives and develop shared understanding among the scenarios.

In the first workshop of phase II, a consensus on six overarching scenario themes—three adaptive and three transformative—emerged from rapid prototyping from a large pool of diverse vision statements. The final scenario themes included: flood resilience, drought adaptation, heat mitigation, food and energy security, eco-city, and zero waste. To develop the adaptive scenarios, participants started with the urban resilience challenges (i.e., extreme flood, drought, and heat identified in phase I and validated in workshop 1) and identified land use and infrastructure solutions to address those challenges. For the transformative scenarios, participants identified ambitious, aspirational, sustainability goals for the year 2060 and then used backcasting techniques to achieve the desired outcomes.

In phase III, we increased the specificity of, and the distinctiveness among, the scenarios through a series of activities developing spatial maps, system maps, timelines, and descriptive narratives and visualizations. Participants drew directly on spatial maps (participatory GIS mapping) the locations for each strategy, and provided descriptions for other spatial characteristics—size, number, connectivity, or the degree of centralization/decentralization. Qualitative rules were also used to describe spatial characteristics not easily represented on the physical maps (e.g., place the trees in the hottest neighborhoods and only along auxiliary streets). In the next activity, participants created system maps (i.e., causal loop mapping) of the co-developed strategies to identify SETS relationships among the strategies. System maps helped participants refine their understanding of the relationships to produce more holistic visions. Then, using timelines the participants described the temporal sequence and linkages of each of the SETS strategies (adaptive scenarios: present day to 2060; transformative scenarios: 2060 to present day). From these initial (focal) strategies, additional supporting strategies were then co-developed. These supporting strategies were included to further detail what would be needed in order to implement the focal strategies or maintain them post-implementation (e.g., for a rainwater collection strategy the supporting strategies may include targeted educational campaigns and financial mechanisms for residential retrofits). For key interventions, the implementation rates were agreed by describing intermediate targets (e.g., 2020 initiative start, 2030–2040 describing < 10–70% implementation, and finally 2045 with complete implementation). Facilitator-led probing questions such as "why, for whom, by whom?" helped to further clarify normative features of the strategies and provided additional reflexivity. Finally, participants developed actor-oriented narratives through participatory storytelling describing the future in 2060 and working with designers to develop visuals, including rendered vignettes of iconic landmarks and animations of the narratives. The final products comprised detailed representations of the transition and implementation pathways from spatial, systems, temporal, and normative perspectives.

In phase IV, we explored sustainability and resilience implications of the scenarios. We co-developed and applied multi-criteria indicators to evaluate the tradeoffs and benefits of each scenario. Quantitatively, we explored future outcomes of land use/land cover (LULC), regional heat, local microclimates, and water use and water availability (Table 1).

In more qualitative assessments, we co-developed indices to assess sustainability, resilience, and equity characteristics. During workshop 6, we conducted a participatory assessment to evaluate how well the scenarios met sustainability, resilience, and equity criteria by comparing associated weights and scores among the scenarios. Finally, we examined the tradeoffs and benefits of each scenario based on the qualitative and quantitative assessments to evaluate key solutions to future challenges. Based on the assessments, we then revised each scenario to better meet the desired outcomes.

3.3. CAP SFS case study: scenario results and outcomes

Here, we here highlight the salient features of the adaptive and transformative scenarios and key results from assessment activities—compared to the strategic scenario. A rich description of each scenario, through GIS maps, transition timelines, design vignettes, model outputs, animated narrations, and comparative evaluations, is available online (http://sustainablefutures.asu.edu).

3.3.1. Adaptive and transformative scenarios

3.3.1.1. Adaptive Flood: Desert wetland. The Adaptive Flood: Desert Wetland scenario explores the application of the "sponge city" archetypal urban vision. This scenario applies a "design with nature" approach and extensive green and blue urban ecological infrastructure to manage future increases in severity of extreme rainfall in the CAP region (Fig. 3). This scenario focuses on increasing hydrological connectivity, water conveyance, and managing stormwater. It features large floodplains and an intricate network of vegetated stormwater basins, canals, and parks for water retention and to hydrologically link neighborhoods. During the most extreme precipitation events, when drainage systems are at risk of flooding, transportation routes become part of a flood drainage matrix with the network of parks and retention basins to reduce flow rates and support infiltration of water.

As a result of extensive green infrastructure, 77% of the region is cooler (up to 3.7 °C lower temperature) than the strategic scenario. Groundwater recharge increases due to increased permeable surfaces—contributing to long-term water security. However, outdoor water use increases significantly to irrigate the extensive green infrastructure, despite retrofitting of household irrigation systems to use non-potable gray water.

3.3.1.2. Adaptive Drought: True Cost of Water. The Adaptive Drought: True Cost of Water scenario explores a future whereby droughts are more frequent, last longer, and occur during extreme heat events. The scenario emphasizes aggressive water conservation targets, centralized infrastructure for stormwater and decentralized infrastructure for water reuse, and water banking for long-term water security. Water conservation occurs primarily by reducing the agricultural land area and restoring it to native Sonoran Desert. With a renewed focus on "desert living" in the urban core, all landscaping, except public parks, incorporates low-water-use xeric or native landscaping that is irrigated primarily by on-site commercial and residential gray water. Finally, high water prices encourage higher-density residential development in previously suburbanized places.

All of these strategies result in a reduction in outdoor water use from traditional potable sources (e.g., Colorado, Salt, and Verde Rivers) compared to the strategic scenario. At the same time, the decrease in mesic vegetation results in a vegetation-water-temperature tradeoff. Temperatures are higher than the strategic scenario in 46% of the region with temperatures up to 2.6 °C higher than the strategic scenario (Fig. 4).

3.3.1.3. Adaptive Heat: Cool it or Lose it. The Adaptive Heat: Cool it or Lose it scenario responds to a significant increase in "unusually hot days" (> 46 °C) by the end of the century. The main strategy to reduce local heat exposure is a large-scale increase in shade and canopy cover, specifically in neighborhoods with high social vulnerability. In this scenario, shade increases 50% by 2060—split equally between desert-adapted trees and gray infrastructure shade. Overall, sprawling development decreases while vegetation and urban density are concentrated along canals. These lower temperature microenvironments encourage walking and the light rail connects people to the growing park network. Most traditional impervious pavement has been replaced with "cool pavement" and other innovative materials that retain less heat.

In the Cool it or Lose it scenario, the adaptive heat strategies lower the regional temperature up to 4 °C compared to the strategic scenario. In order to maintain the lower temperatures, irrigating vegetation is prioritized over groundwater banking for long-term security.

Table 1
Models and methods for scenario exploration (phase IV).

Models	Descriptions	References
Participatory land use/land cover (LULC) change model	30 m Landsat TM downscaled to 15 m resolution with National Agricultural Inventory Program (NAIP) data	Li et al., 2014
Weather Research and Forecasting (WRF)	Process-based mesoscale climate model, 5 AM mid-July heat wave	Georgescu, 2015; Georgescu, Moustaoui, Mahalov, & Dudhia, 2011; Skamarock & Klemp, 2008
Microclimates	Microscale & thermal comfort modeling calibrated from field observations	Middel, Chhetri, & Quay, 2015; Middel, Häb, Brazel, Martin, & Guhathakurta, 2014; Middel, Selover, Hagen, & Chhetri, 2016
WaterSim	Model relating water supply & delivery under futures of population growth & climate change	Sampson, Quay, & White, 2016

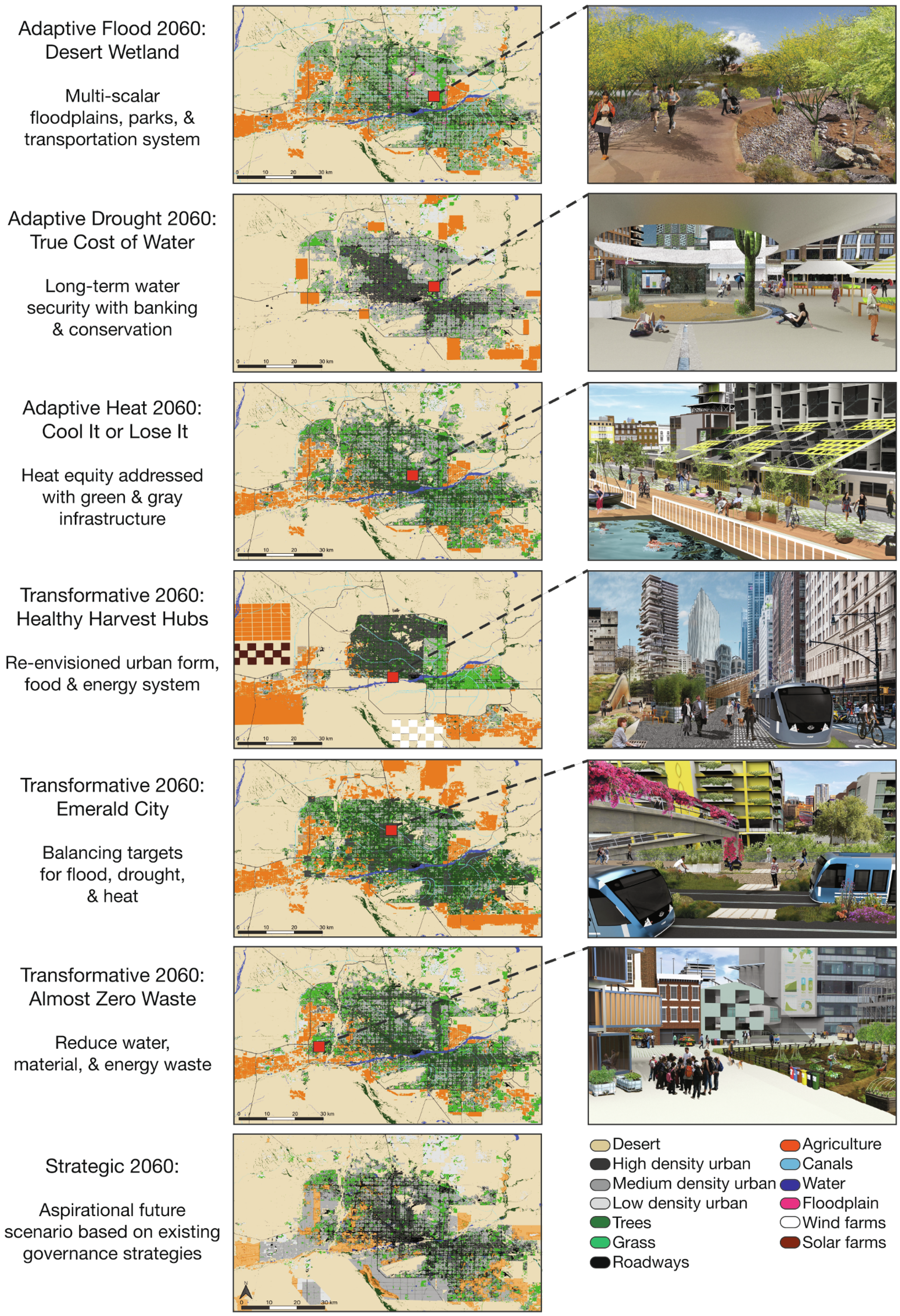

Fig. 3. Future land use/land cover outcomes of each scenario. Design vignettes were developed from the scenarios at specific locations (red squares). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3.1.4. Transformative: Healthy Harvest Hubs. The Healthy Harvest Hubs scenario explores changes to urban form and density that address energy security, food security, and transportation efficiency. New urban and agricultural hubs are intended to optimize city function. Urban hubs vary in density: “garden hubs” contain medium-density single and multi-family housing with dispersed community gardens; the “central city hub” features dense development, high-rise condos, little open space, and a knowledge-based economy; “agricultural hubs” located along rivers grow water-efficient crops and produce food for the regional population. Outlying open spaces and “agricultural hubs” are connected to the urban core by trails and a light rail, which have replaced the existing freeway system; there are no personal cars in this future.

The land use changes in Healthy Harvest Hubs result in lower

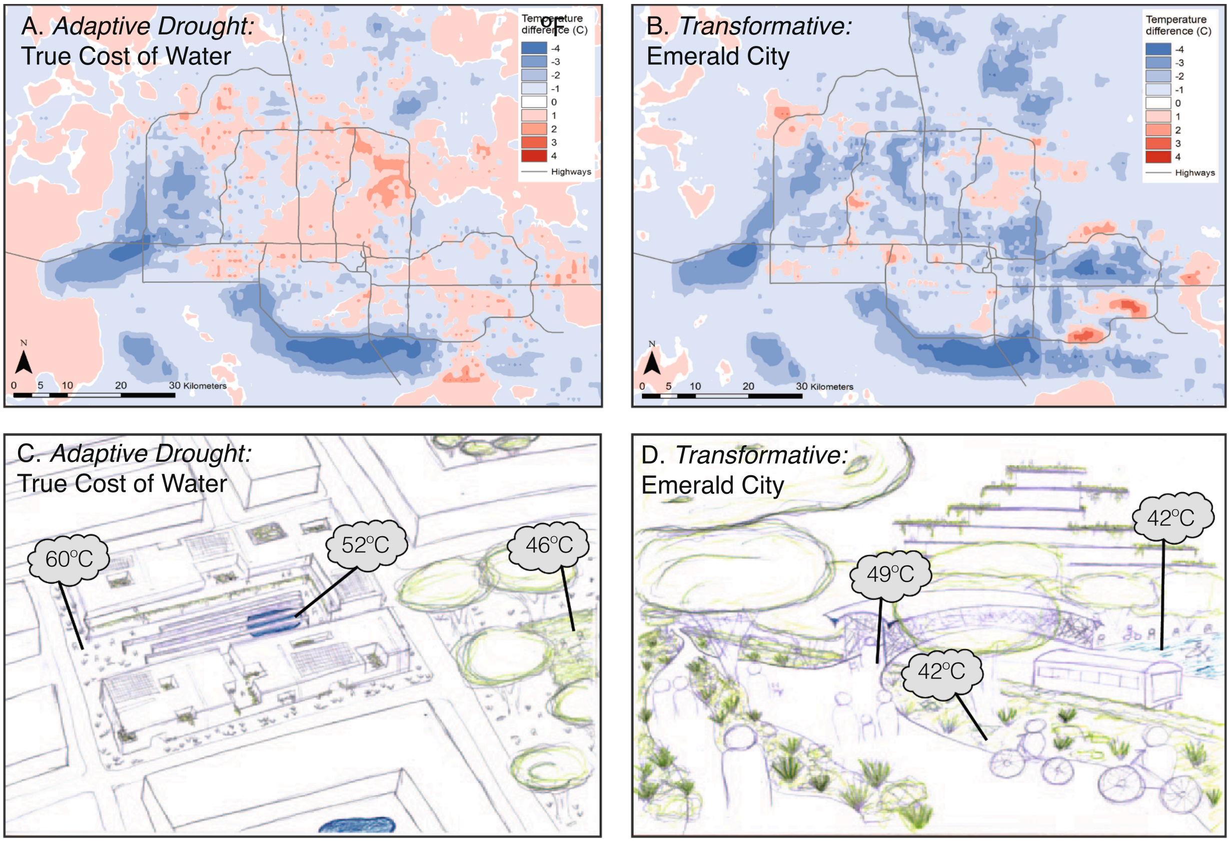

Fig. 4. Regional heat at 5 AM for Adaptive Drought: True Cost of Water (A) and Transformative: Emerald City (B) relative to strategic Scenario from regional WRF model. Microscale thermal comfort for True Cost of Water (C) and Emerald City (D) scenarios. Microclimate temperature represents thermal comfort for specific locations in the region. In the workshop setting, microclimate was used to explore the implications of heat strategies.

regional temperatures up to 5.6 °C compared to the strategic scenario as a result of conversion of urban land to desert, no new urban expansion, and extensive green infrastructure in the "garden hubs". However, the high density of the "central city hub" results in similar (sometimes higher) temperatures compared to the strategic scenario. There is an increase in alternative water sources for irrigation, while traditional water sources are used indoors.

3.3.1.5. Transformative: Emerald City. The Emerald City scenario balances tradeoffs that address flood, drought, and heat risks through changes to land use and urban form. This transformative scenario utilizes decentralized infrastructure to capture rain, storm, and gray water for on-site irrigation and to alleviate the pressure on potable water sources. This scenario's iconic feature is the repurposing of 75% of 2015 existing freeways into greenways. The canals and new greenways support a multi-modal transportation network of light rail, bicycle, and pedestrian infrastructure. The region's overall canopy cover is 25% and heavily concentrated within the greenway system. Building designs support vegetation, provide shade, and other cooling opportunities. Finally, growth boundaries encourage inward and vertical development concentrated at intersections of the multi-modal transportation network.

Overall, the Emerald City scenario has a lower regional temperature (up to 3.7 °C lower than the strategic scenario in 71% of the region, Fig. 4) and uses the least water from traditional sources due to aggressive indoor water conservation and outdoor water use from alternative sources.

3.3.1.6. Transformative: Almost Zero Waste. The Transformative: Almost Zero Waste scenario focuses on increasing self-sufficiency and minimizing waste. This is achieved through aggressive targets for conservation, capture, reuse, and recycling to reduce reliance on traditional water and energy sources. Residents of this future live within twenty minutes of 80–90% of their needs in high-density urban cores and mixed-use developments that are concentrated along public transportation corridors. Urban vegetation and gardens are maintained with neighborhood compost and gray water "smart" irrigation systems using 100% reclaimed water. The scenario relies on decentralized local recycling and solar infrastructure to provide 100% of energy demand. At the same time, the centralized municipal-scale stormwater infrastructure banks water for future use.

Overall, regional temperatures of this future are lower than the strategic scenario due to the decrease in sprawl and increase in distributed agriculture throughout the city. As a result of aggressive water conservation, capture, and re-use strategies, nearly 90% of outdoor water use is sourced from alternative sources by 2040.

3.3.2. Cross-scenario comparisons

The strategic scenario—the future scenario developed from existing municipal plans and goals—was used as a baseline for the comparison among the six co-produced alternative future visions for the CAP region. We specifically contrasted key differences with local and regional implications, including quantitative differences in LULC, regional temperature, microclimate, water conservation, and water banking (Figs. 3–5) and qualitative features addressing sustainability, resilience, and equity (Table 2).

Changes in urban form, and the resulting impacts on temperature and water use, vary dramatically among the 2060 scenarios. For example, in Emerald City, urban development is concentrated along new green corridors, while in other scenarios, development is concentrated within high-density urban centers (e.g., Healthy Harvest Hubs, True Cost of Water; Fig. 3). These and other LULC changes, including

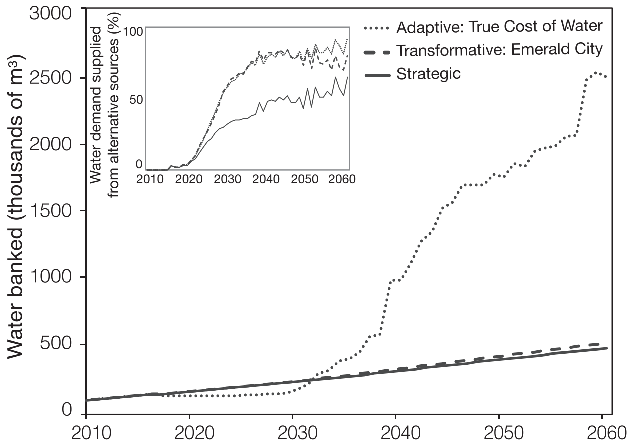

Fig. 5. Water banked ($\times$1000 of m^3) and water demand supplied from alternative sources (percent, inset figure) between 2010 and 2060 for Adaptive Drought: True Cost of Water, Transformative: Emerald City, and the Strategic 2060 scenario as a result of diverse strategies to improve future water security. Alternative water sources include captured rainwater, gray water, and reclaimed water.

agricultural land redistribution, floodplain designations, and restoration of desert open space, result in tradeoffs of regional cooling and water conservation. For instance, in Healthy Harvest Hubs, large decreases of impervious surface and increased desert land on the periphery of the urban core result in significant regional cooling (Fig. 4). Emerald City, on the other hand, achieves a reduction in regional temperature from a substantial increase in green infrastructure throughout the region. In comparison, water conservation measures, such as reduced outdoor vegetation and reduced irrigation in the drought scenario, True Cost of Water, result in higher temperature (Fig. 4).

Whether to support on-site green infrastructure or achieve aggressive potable water conservation goals, all six co-produced scenarios increase the use of alternative water sources (e.g., rainwater, gray water, reclaimed water) for outdoor water needs. Both the Adaptive Drought: True Cost of Water and Transformative: Emerald City scenarios emphasize aggressive water conservation, water collection, and water banking as key regional strategies. However, the True Cost of Water scenario focuses on centralized stormwater infrastructure and gray water piping to ensure long-term water security (Fig. 5). In contrast, Emerald City emphases decentralized water harvesting and infiltration-based banking to support green infrastructure, which also contributes to ameliorating heat stress across the region.

In addition to comparisons of heat and water tradeoffs, participants assessed the strategic and co-produced scenarios in terms of their sustainability and resilience characteristics. Participants developed indicators, weights, and metrics and then scored each scenario. The indicators were grouped into social, ecological, technological categories—equitable city (social dimension), eco-city (ecological dimension), and smart city (technological dimension)—and indicators of resilience to future extreme drought, flood, and heat. Resilience indicators addressed qualities of systems resilience (e.g., adaptive learning, diversity, redundancy) and specific adaptive capacities associated with each extreme event. Each scenario was scored by workshop participants—first as individual participant scores, negotiated in small groups, then discussed in plenary. All scores were benchmarked in comparison to the strategic scenario with scores ranging from −3 (much worse) through 0 (similar) to +3 (much better). The assessment was based on expert judgement for aspects of the scenario when supporting quantitative data or models could not be provided by the researchers or practitioners involved. Not surprising for a desert city, the initial scoping and framing focused on heat and water. However, any number of SETS dynamics may be quantitatively modeled to support expert judgments.

In most cases, the co-produced scenarios scored higher than the strategic scenario (Table 2). The overall scores ranged from 3.7 to 12.3 (out of a possible 18 points) with mean = 9.3 (SE = 1.22). Thus, all six co-produced scenarios were perceived as an improvement compared to the strategic scenario constructed from planning documents. The Transformative: Emerald City scenario was given the highest overall score and outperformed the strategic scenario in every category. By contrast, the Adaptive Drought: True Cost of Water scenario received the lowest overall score. This scenario performed the same as or worse than the strategic scenario with respect to coping with heat, coping with flooding, and for the equitable city indicators, but scored highest in addressing drought. All scenarios scored low on equity indicators (i.e., equitable city). Overall, the True Cost of Water scenario had a notably lower score for resilience (1.8 compared to all others > 5.50 of 9.00) and sustainability indicators (1.9). The transformative scenarios (Healthy Harvest Hubs, Emerald City, and Almost Zero Waste) performed much better on the sustainability indicators than all three adaptive scenarios (Table 2).

4. Discussion and conclusions

The SFS initiative was developed as a transdisciplinary research-practice approach to co-produce future scenarios that bring together diverse knowledge systems represented by participants to deliberately contrast plausible-desirable visions of sustainability and resilience. The distinction between plausible and desirable future visions can create tension between research and practice in resilience and sustainability planning (Bai et al., 2016; Wiek & Iwaniec, 2014). The SFS framework exploits this tension with three distinct scenarios—strategic, adaptive, and transformative scenarios—in order to create an opportunity to explore a continuum of possibilities from plausible to desirable (Fig. 1). The SFS strategic scenarios primarily emphasize what is plausible—or

Table 2
Participatory assessment of the co-produced scenarios compared with strategic scenario (score = 0) on a scale of −3.0 (worse than strategic) to + 3.0 (better than strategic) in terms of resilience (ability to cope with flood, drought, and heat) and sustainability (equitable city, eco-city, smart city). Best performing scenario is in bold for each indicator set and the sum of resilience (RESIL), sustainability (SUST), and overall (Overall).

	Resilience characteristics			Sustainability characteristics			Summary scores		
	Cope with flood	Cope with drought	Cope with heat	Equity City (S)	Eco City (E)	Smart City (T)	RESIL	SUST	Overall
Adaptive scenarios									
Flood: Desert wetland	**3.0**	2.0	1.5	0.0	2.0	0.0	6.5	2.0	8.5
Drought: True Cost of Water	0.0	**3.0**	−1.3	−0.8	1.0	1.8	1.8	1.9	3.7
Heat: Cool It or Lose It	1.5	2.0	**3.0**	0.8	2.0	1.0	6.5	3.8	10.3
Transformative scenarios									
Healthy Harvest Hubs	1.5	2.0	2.0	0.5	1.5	**3.0**	5.5	5.0	10.5
Emerald City	2.5	1.8	2.5	**1.8**	**2.8**	1.0	**6.8**	**5.5**	**12.3**
Almost Zero Waste	2.0	2.5	2.0	1.0	2.0	1.0	6.5	4.0	10.5

what is more likely to happen in the future—as they are projected from existing governance strategies. However, they too represent aspirational, positive futures with policies and strategies that may or may not be implemented. Adaptive scenarios are problem-oriented and explore how to be more resilient in the face of future challenges such as increasingly frequent extreme flood or drought events. Transformative scenarios, on the other hand, emphasize normative goals, following the tenets of sustainability science, that would result in persistent, fundamental changes to the status quo (Iwaniec, Cook, Barbosa, & Grimm, 2019). In this way, transformative scenarios place a stronger emphasis on the desirability of the pathway—beyond what is merely plausible and instead focused on big, radical goals. With the strategic scenarios serving as a baseline, the adaptive and transformative future visions can be contrasted to understand the range of possibilities and potential unintended tradeoffs. The alternative SFS scenarios allow stakeholders to explore pathways to close the gap between the future goals that are plausible and those that are desirable transformative changes.

Along with understanding plausible and desirable future goals, resilience and sustainability principles are key to developing adaptive and transformative pathways of change (Folke, Carpenter, Walker, & Scheffer, 2010; Pelling, 2010; Redman, 2014; Romero-Lankao et al., 2016; Wiek & Iwaniec, 2014). From resilience thinking, adaptive changes are incremental responses to shocks that maintain previous structure and function and rely on emergent properties to guide future trajectories (Redman, 2014). From sustainability science, transformational pathways include elements of major fundamental change that create new system dynamics (Redman, 2014; Leach, Scoones, & Stirling, 2010). Both resilience and sustainability principles are incorporated into the SFS approach of developing and assessing adaptive and transformative scenarios. For example, in the CAP case study, the adaptive scenarios scored higher for resilience characteristics to specific challenges (e.g., drought in True Cost of Water), while the transformative scenarios scored higher for sustainability characteristics (Table 2). The fundamental change in the systems-based characteristics of the transformative scenarios (e.g., change in underlying values around car ownership in the Transformative: Healthy Harvest Hubs scenario) explains the higher ranking for sustainability characteristics. The resilience and sustainability assessments highlight that targeting specific adaptive capacity does not necessarily ensure general adaptive capacities or general resilience (Eakin, Lemos, & Nelson, 2014; Carpenter et al., 2012). Adaptive scenarios offer the opportunity to develop adaptive capacity in response to a particular stress, while otherwise maintaining the system order (Redman, 2014). On the other hand, transformative scenarios build agency, leadership, and change agents with a focus on anticipatory actions in advance of major stresses.

Systems approaches are essential for evaluating relationships among alternative sustainability and resilience pathways. The SFS approach explores tradeoffs and synergies among distinct goals and social, ecological, and technological strategies through creative methods of representing and evaluating scenarios. It integrates quantitative and qualitative evaluation of hypotheses—by both practitioners and researchers alike—about what the future may look like or how SETS components may interact. For example, in the CAP case study, participants examined a wide array of strategies in phases III and IV for centralized and decentralized governance structures, equity, land and water conservation, and integrated bike-rail-canal transportation systems. Rather than relying solely on expert-based evaluations, scenarios were evaluated in participant-led, evidence-based assessments. Participatory evaluation not only ensures that the values of the stakeholders remain at the forefront of the process, but it also serves as a tool to strengthen relationships among participants.

Recent work in sustainability science embraces transdisciplinary approaches and participatory, solutions-oriented, knowledge production to develop innovative strategies addressing future challenges (e.g., Miller & Wyborn, 2018; Clark, van Kerkhoff, Lebel, & Gallopin, 2016; McPhearson et al., 2016; Lang et al., 2012). Contributing to sustainability science, the SFS approach moves beyond consultative forms of public engagement to creatively engage stakeholders in consensus building around shared visions for the future (e.g., Few, Brown, & Tompkins, 2007; Arnstein, 1969). Using the SFS approach can create true collaborations among stakeholders. The activities integrate research and practice goals, build trust, and incorporate deliberation and negotiation. In the CAP case study, collaborative relationships established during the workshop series have persisted in the form of new projects and continued engagement in further scenario work at a smaller scale. Through the co-production of scenarios, we address surprise, disagreement, confusion, objections, and other critical elements of rich scenario processes. In the CAP workshops, there were instances of verbal conflict among participants from different cities within the region, perhaps reflecting actualized future tradeoffs and the inter-municipality competition that sometimes underlies regional planning. Another example was the surprise generated when water-banking strategies, which were perceived to be innovative, failed to produce the desired water savings. The SFS approach builds capacity for creating shared positive futures that are inspirational.

Visions alone are not sufficient for catalyzing transformational change; the shared visions need to be incorporated into programs and policies. The SFS process enhanced research, policy, advocacy, and decision-making at multiple scales in the CAP region. From a research perspective, the SFS participatory process was an opportunity to synthesize diverse forms of knowledge and data about the CAP SETS. While the CAP scenarios are not expected to become a future reality in their entirety, the regional challenges will likely become reality. The SFS process helped build relationships among stakeholders from diverse sectors, cities, and scales who do not typically work together. Moreover, the strategies developed in the SFS workshops are being incorporated explicitly in the City of Phoenix Sustainability Plan as a direct outcome of the participation of the Chief Sustainability Office for the City of Phoenix.

The application of the SFS approach as described here can be a useful complement to traditional projection modeling. Although the SFS approach does not purport to predict future urban changes, it allows teams to ask "what if" questions, such as, how the implementation of different adaptive strategies, continued urban growth, or changes in urban form interact with projected climate changes. The SFS process generates future land cover and infrastructure configurations that can be tested via models (e.g., regional heat and water use) to reveal consequences and potential trade-offs of key strategies in a city or region. There is not one, not two, but a universe of possible futures. Thus, integrating diverse perspectives, evidence, and human values through the SFS process allows stakeholders to explore future conditions that would not be possible with a strict modeling approach.

Solving future resilience and sustainability challenges for cities will require anticipatory planning and long-range visioning. Yet, urban planners and decision-makers often prioritize easily implementable targets and short-term accomplishments within their term limits. Opportunities to think beyond these constraints are relatively rare, but they are essential for imagining innovative solutions to future challenges (McPhearson et al., 2016). The SFS framework addresses the need to envision long-term futures, while also creating opportunities for researchers and practitioners to explore a range of short- and long-term pathways and innovative solutions. The process of co-producing and evaluating scenarios builds anticipatory, long-term, and systems-based thinking capacity among participants (Carpenter et al., 2015; Ramirez, Mukherjee, Vezzoli, & Kramer, 2015; Sheppard et al., 2011; Wiek & Iwaniec, 2014). With these key capacities, cities will increase their agency to successfully implement future resilience, sustainability, and transformational change initiatives (Iwaniec et al., 2019; Romero-Lankao et al., 2016; Wolfram, 2016).

CRediT authorship contribution statement

David M. Iwaniec: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Elizabeth M. Cook:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Melissa J. Davidson:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft. **Marta Berbés-Blázquez:** Investigation, Writing - original draft. **Matei Georgescu:** Formal analysis, Writing - review & editing. **E. Scott Krayenhoff:** Formal analysis, Writing - review & editing. **Ariane Middel:** Formal analysis, Writing - review & editing. **David A. Sampson:** Formal analysis, Writing - review & editing. **Nancy B. Grimm:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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