



Compound[ing] disasters in Puerto Rico: Pathways for virtual transdisciplinary collaboration to enhance community resilience

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ABSTRACT

Puerto Rico has been subject to complex and compounding effects of multiple disasters, exacerbated by socio-political, climatic, and geographical challenges that complicate relief and resilience. Interdisciplinary teams are uniquely suited to traverse emerging challenges in post-disaster settings, but there are few studies that leverage transdisciplinary skill sets and virtual co-production of knowledge to build on local autonomous responses. Communities are key sources of information and innovation which can serve as a model for recovery amidst disaster. Thus, an interdisciplinary team of emerging scholars collaborated with Caras con Causa, a local organization in Cataño, Puerto Rico, to develop processes for enhancing autonomous responses to disaster events through participatory pathways, specifically highlighting local knowledge and preferences. The results of this collaboration include: (1) an iterative process model for transdisciplinary co-production in virtual settings and (2) key highlights from post engagement reflections including community-scale definitions of disaster, and limitations to virtual collaboration amidst disaster. Together, these results yielded critical insights and lessons learned, including recommendations for improved project communication methods within transdisciplinary and virtual collaborations. Collectively, the process, its resulting products, and the post-engagement reflections demonstrate a pathway for scholars and community members to engage disaster resilience challenges. These strategies are most effectively practiced through focused collaboration with community stakeholders and are paramount in solving real-world challenges related to the increasing complex of compounding disasters.

1. Introduction

It is increasingly necessary to prepare for multiple, overlapping disasters as the world navigates towards a climatically unstable future, wherein geographically predisposed areas are likely to experience the compounding effects of multiple hazards within increasingly shorter timescales (Buma, 2015; Cutter, 2018). Compounding disasters in this context refers to multiple disasters occurring simultaneously or in close succession, whose combined effects overwhelm local capacity to respond or recover (Liu and Huang, 2014). Since characterizing an event

as a disaster requires social context (Kelman, 2019), we broadly define disaster as the extent of harm following an event(s), natural or otherwise, which impact livelihood, reduce quality of life, and disrupt existing Food, Energy, Water (FEW) systems. The cascading effects of compounding disasters have direct impacts on critical infrastructure, services (e.g., healthcare) and essential resources, thereby exacerbating vulnerabilities and injustices, leaving dire consequences for the most vulnerable populations (Pescaroli and Alexander, 2016; García et al., 2021). These disruptive events often escalate from something anticipated, prepared for, and seemingly manageable into more complex

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problems as hazardous events become connected and compound (Cutler, 2018). As each combination of hazards and events impact communities and their FEWS systems in distinct ways, multi-layered disasters require unique recovery decisions and plans. Yet, academic and industry perspectives of disaster are incomplete unless they account for and incorporate the lived experience of those directly impacted.

Given the complex nature of disaster relief and resilience, a transdisciplinary approach that integrates scientific and local knowledge is crucial for reducing vulnerability and increasing adaptive capacity (Bendito & Barrios, 2016). Virtual collaborations that implement project management and database tools are particularly well-suited to facilitate trust-building and innovative engagement between interdisciplinary groups of researchers and otherwise inaccessible communities, thereby sharing responsibility for team goals on complex, interwoven tasks, despite geographic barriers and limited in-person contact (Malhotra et al., 2007). The uncertainty associated with compounding disasters elevates the role of trust throughout recovery processes, yet globally mounting calls for resiliency suggest an onerous shift from collaborative processes towards community self-reliance and self-preparedness in the wake of devastating, compounding disasters (Bonilla, 2020a, 2020b). Transdisciplinary collaborations have the potential to facilitate effective risk assessments, spur dialogues, and drive actionable initiatives; yet few frameworks modeling the bridge between bottom-up and top-down initiatives exist (Gaillard and Mercer, 2012; though see Mercer et al., 2009). While previous scholarship has separately elaborated on both transdisciplinarity in disaster relief and virtual, knowledge co-production, there is little research on how to combine the two to strengthen local and preexisting capacities for disaster resilience. To address this gap, our work examines how communities and researchers can collaboratively build on emerging autonomous responses throughout ongoing disasters, with a particular focus on virtual, transdisciplinary teamwork for enhanced resilience and disaster preparedness.

This research is rooted within the context of FEWS systems in Puerto Rico. Our aim was to create a collaborative system between transdisciplinary researchers and Caras Con Causa, a non-profit group, to better implement strategies related to disaster relief and resilience (DRR). This research specifically addressed the questions of (1) how communities and researchers can collaboratively bolster pre-existing autonomous responses in the context of compounding disasters, and (2) what advantages and disadvantages there are to virtual, transdisciplinary teaming on such ventures. Ultimately, our team of scholars and local stakeholders, including organization and community leaders, co-produced a framework to strengthen community resilience and enhance decision-making capacity in response to disaster related events. Post engagement reflections further reveal pivotal moments upon which virtual, transdisciplinary collaborations in disaster contexts can be improved. These results highlight lessons learned and critical insights to enhance strategies for virtual, transdisciplinary collaboration amidst compounding disasters.

2. Literature review

2.1. Disaster resilience and autonomous response (in Puerto Rico)

Resilience, in a disaster setting, is more appropriately defined at the scale of the community and represents the system's ability to adapt and 'bounce-forward,' allowing for growth in a new direction (Serrano-García, 2020). It suggests a sustained effort to equitably prevent disaster by a collective entity (Gaillard and Gomez, 2015) and is often an emergent property dependent on cultural traits and any systemic injustices present within a region (Serrano-García, 2020). Resilience is not an innate characteristic nor a linear trajectory, but rather something to be honed with time and facilitated through robust communication methods. Indeed, development of societal resilience is complex and adaptive, rather than a one-time investment in the

immediate aftermath of a hazard, because disasters can both create new forms of resilience by strengthening community and destroy old forms of resilience (and trust) by unveiling incompetency and bias (Bonilla, 2020a). Moreover, a single 'weak link' does not influence total resilience, and high resilience is characterized by strong networks, infrastructure, and cultural identity (Serrano-García, 2020). Robust societal resilience is critical to stave off disaster by protecting vulnerable communities and essential FEWS resources. Thus, the relationship between disasters and FEWS systems is transient, and certain definitions of resilience that do not consider the ever-changing nature of community response to disaster can obscure the complexities of each scenario.

Disaster risk management programs are now more focused on building adaptive capacity and resilience at the community level (Canevari-Luzardo et al., 2017). However, vulnerable populations are not often prioritized and may lack sufficient information or resources to adapt to risk themselves; one way this is explicitly visible is in the case of informal settlements (Woodruff et al., 2018). At the same time, local organizations are often at the center of efforts to promote community resilience, yet limited time and resources can quickly exhaust capacity for collaboration. Therefore, it becomes important to understand what role academics can play in supporting community resilience throughout multiple hazards without presenting a strain on local resources. Unlike federal bodies, grassroots organizations are more connected to local issues and are better positioned to mitigate and alleviate the disaster challenges posed to external or national agencies (Pelling, 2007; Serrano-García, 2020). In fact, the concept of *autogestión*, or autonomous response, saw a surge in popularity prior to Hurricane Maria and was further magnified throughout recovery in Puerto Rico (Bonilla, 2020a). In the context of disaster, autonomous response refers to initiatives that emerge from and are led by communities for the wider community's recovery and subsequent disaster preparedness. After Hurricane Maria, *autogestión* came in many forms, including community-formed advocacy groups, local organizations taking on new roles to fit gaps left by established recovery systems, and communities creating important social networks to check on the more vulnerable members of the community (Rodríguez Soto, 2020). When speaking of *autogestión* or autonomous response, we are alluding to initiatives communities have coordinated independently, whereas reference to anything "community-based" was achieved collaboratively in partnership with a particular community.

Due to their distinct responses to the recent and overlapping disaster scenarios, Puerto Rico is a node for innovation in disaster recovery. Van Niekerk and Annandale (2013) argue toward "enhancing the skills, knowledge, and capacities of local communities" to reduce disaster risk (p. 164). It becomes critical to understand how individual and community recovery can be effectively supported (Talbot et al., 2020). Moreover, scholars emphasize the value of community-driven efforts and organization based on the knowledge that community resilience is critical for disaster recovery processes - especially in light of state abandonment (Bonilla and LeBrón, 2019; Ficek, 2018; Lloréns & Stanich, 2019). State abandonment in Puerto Rico is often characterized by the entrenchment of neoliberal disinvestment, leading to purposeful neglect of the archipelago's needs (Atilas, 2021). For example, a study by the NRDC (2017) reveals "that in 2015, 99.5% of the population obtained water from systems that violated the Environmental Protection Agency's health standards—a direct result of the debt crisis" (Ficek 2018: 113). Throughout nine months in the aftermath of the 2017 hurricanes, people organized across heterogeneous networks for survival and self-provision in place of failing or inoperable infrastructure (Ficek, 2018; Roque et al., 2021). The urgent necessity to coordinate beyond the state further elucidates why community resilience is central to effective disaster recovery.

2.2. Enhancing traditional methods for DRR through virtual transdisciplinarity

Disaster recovery exists in a unique intersection of the social and biophysical sciences, however, deep knowledge integration between these disciplines has historically been constrained by a lack of collaboration (Braunisch et al., 2012). Transdisciplinary projects combine the approaches and perspectives aimed to transcend both diverse disciplinary boundaries and the epistemic divide between communities and the academy. In disaster settings, transdisciplinarity allows for more holistic, meaningful, and appropriate outcomes to emerge. Such collaborative approaches should also be pluralistic, dynamic, and evolving toward fusing disciplinary epistemologies in order to address real-world problems (Wickson et al., 2006). As explained by the United Nations, “we need to adopt pragmatic, pluralist approaches that can study risk phenomena at a variety of levels... we should redesign our research methodologies to operate in a transdisciplinary manner” (UNDRR, 2019, p. 8). An ideal transdisciplinary process should continuously and simultaneously build contextual awareness for the academic team and build capacity in the partner community, as these specific intentions encourage greater mutual understanding and increase collaborative impact (Lang et al., 2012).

Indeed, top-down disaster risk approaches often fail vulnerable communities due to a lack of thorough understanding of exposure, vulnerabilities, and resilience at the local scale (Van Niekerk et al., 2018). For example, hazard mapping tools have traditionally been used by ‘experts’, rather than communities, who often construct their own version of reality and priorities rather than representing the experiences of community members (Radil & Anderson, 2019). Given that maps can exemplify transdisciplinary data, they can also serve as “boundary objects” for building shared understandings around vulnerability and risk (Walters et al., 2019; Canevari-Luzardo et al., 2017). Researchers now agree that communities affected by disasters are the most important font of information for risk and vulnerability, and engaging them directly empowers communities to approach issues from the perspective of their own experiences (Van Niekerk et al., 2018). It is important to also involve community members in risk identification, data collection, or data analysis, or in all such activities (McCormick, 2012). While coproduction of knowledge is recommended for the development and implementation of innovation in disaster risk reduction, there is little consensus about what co-production means, how it is practiced, or its impacts (Filipe et al., 2017; Izumi et al., 2019; Mach et al., 2020).

After researching the role of participatory mapping in disaster risk reduction, Cadag and Gaillard (2012) suggest that stakeholder collaboration and knowledge co-production are fundamental for sustainable disaster risk reduction initiatives. Thus, making space for local knowledge and fostering an awareness of the potential burdens of collaboration is key to co-producing actionable and effective knowledge practices between academics and practitioners (Arnott et al., 2020a; Dewulf et al., 2020; Latulippe and Klenk, 2020). Furthermore, fostering culturally appropriate disaster relief and resiliency is a deeply iterative process incomplete without community engagement (Amaratunga, 2014). Citizen science has been proposed as an effective means to increase public participation specifically in environmental research (Dickinson and Bonney, 2012), and some studies have emphasized its potential socioeconomic impact and benefits for both local and global disaster risk assessment and data archiving (Pelling, 2007). These findings reflect a paradigm shift occurring in disaster science, from institutionally developed single hazard research to transdisciplinary, and co-produced multi-hazard research (Ismail-Zadeh et al., 2017). However, within disaster research specifically, transdisciplinary co-produced knowledge wherein non-academics participate in project design, execution, and publication remains limited (Gall et al. 2015 - though see van Manen et al., 2015; Varma et al., 2021). Creating space for local knowledge within each stage of knowledge creation is an important step towards acknowledging local rights to knowledge, and accurate portrayals and

analyses of complex local issues (Latulippe & Klenk, 2020).

Furthermore, current literature identifies a gap in understanding how the medium of interaction and collaboration impacts the co-production process, e.g., in-person, virtual, (Arnott et al., 2020b; Dewulf et al., 2020; Latulippe and Klenk, 2020). Meaningful transdisciplinary research must often also overcome distance between team members or lack of access to study areas and community stakeholders. While scholars have previously established a positive link between community engagement and the production of usable knowledge, Lemos et al. (2019) demonstrate that face-to-face interaction is not always a necessary component of such exchanges but instead is highly dependent on the anticipated outcomes and the type of information used. Moreover, remote teams have even greater potential to combine geographically dispersed experts, communities, and stakeholders in order to amplify the effects of transdisciplinary efforts, justifying such organization and implementation (Rodríguez et al., 2006). Regardless of collaborative status (virtual or collocated), trust is a foundational element for successful co-production of knowledge (Djenontin & Meadow, 2018). Indeed, in investigating the role of knowledge sharing and trust in virtual collaborations, Alsharo et al. (2017) find that knowledge sharing fosters trust in virtual collaborations. As previously demonstrated for health practices, virtual engagement is especially advantageous for working with distant communities, and those burdened by compounding disasters (Meyer et al., 2005). Virtual collaborations (e.g., virtual teams, global virtual teams, distributed collaborations, science collaboratories) can also function to decrease monetary costs, save time, and lower the environmental impacts that meeting face to face may propagate (Dale et al., 2010), while serving the purposes of transdisciplinary disaster relief and resilience efforts. Thus, our virtual transdisciplinary collaboration approach is based on sharing and co-creation between our academic team and the community. This collaborative approach established a system to iteratively build both context and capacity in both the academic team and our community partners (Fig. 1).

3. Case study area

As seen in the case of Puerto Rico, disasters can and do compound upon one another, requiring that they be considered cumulatively and holistically rather than as a singular event in time (Fig. 2). Models suggest the Caribbean archipelago of Puerto Rico is increasingly at risk of anywhere between one and eleven feet of sea level rise by 2100 (USGCRP, 2018), threatening thousands of residents who live in coastal areas, as well as critical infrastructure situated along the coast (Amiri, 2018; Nunn, 2013). Rising sea temperatures raise the risk of increasingly frequent hurricanes like Maria & Irma (Amiri, 2018; USGCRP, 2018), the compounding effects of which caused extensive disruption and damages to water supply, transportation and road networks, food supply, electricity, medical care, and communication (Pasch et al., 2017; Santos-Lozada & Howard, 2018). Although the number of excess deaths from these hurricanes are disputed, different studies estimate deaths from the impacts of Hurricane Maria to be as high as 4645 (Kishore et al., 2018; Rivera and Rolke, 2019; Spagat and van Weezel, 2020; NIST, 2020).

Moreover, Puerto Rico, situated between the Caribbean and North American tectonic plates, experienced a spike in tectonic activity resulting in over 2500 seismic events between December 28, 2019 and mid-2020 alone (López et al., 2020). The numerous earthquakes and their aftermath challenged building integrities, leading to vast school closures, insecure residences, and further infrastructural erosion (Bonilla, 2020a). Damage to local energy infrastructure left residents without power, again, for several days (Gallucci, 2020). In addition to geographic hazards, global events such as the ongoing COVID-19 pandemic compound the effects of previous disasters and create increasingly hazardous living conditions (García et al., 2021). The ongoing recovery from Hurricanes Irma and Maria in 2017 faced

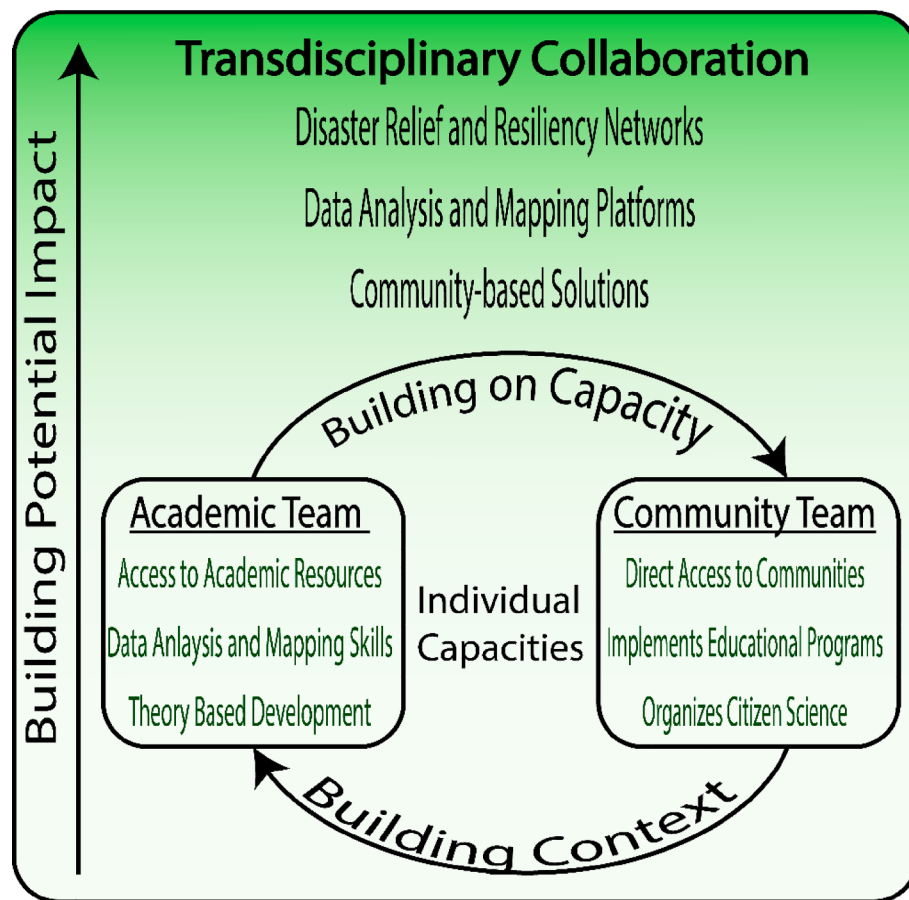


Fig. 1. Demonstration of collaborative strengths between academic and community teams for iteratively building awareness of local contexts and capacities to increase potential impact in transdisciplinary projects.

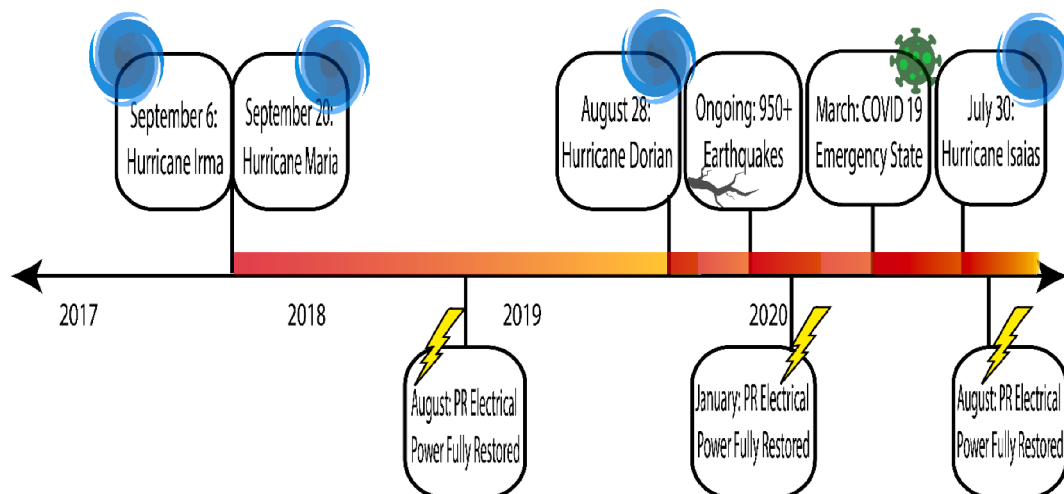


Fig. 2. A timeline demonstrating the compounding effects of disaster events. The colors allude to the overlapping recovery stages proposed by Haas et al. (1977) (red: emergency response; orange: restoration; yellow: replacement reconstruction; green: major reconstruction). In Puerto Rico, full recovery is continuously delayed by the onset of new disasters. Each cluster of disasters disrupts the availability and distribution of power - as evidenced by the numerous efforts of the Puerto Rico Electric Power Authority (PREPA) to restore power. This figure illustrates PREPA's Twitter announcements of power restoration and may not reflect the full conditions on the ground. As the Food, Energy, Water nexus is deeply connected, representations of energy loss also act as a proxy for disruptions to food and water, for which reliable data is scarce. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

setbacks due to the serious earthquakes in early 2020 and when the COVID-19 pandemic required residents to quarantine in homes that were still largely unsafe to live in.

These compounding disasters are preceded by key historical factors

that contribute to their catastrophic impacts, most notably Puerto Rico's relationship with the U.S. (Frittelli, 2019; Rivera, 2018; Caban, 2018; Fonseca, 2019; Caban, 2019). For example, as a result of their long colonial history, Puerto Rico imports approximately 85% of its food

Table 1
Stakeholder backgrounds and relevant research skillsets in virtual, transdisciplinary collaboration.

Stakeholder	Knowledge Background; Discipline Specialization	Research Interest, Skillset
<i>Project Advisors</i>	Agricultural and Biological Engineering; Political Science; Sociology; Agricultural Education and Extension	Graduate Program Development; Transdisciplinary and Project-based Practices
<i>Cohort Challenge Scholars</i>	Agricultural and Biological Engineering, Civil Engineering, Ecology and Environmental Sciences, Anthropology, Political Ecology, Sociology	Geospatial analytics, Community-based research, Disaster recovery, Systems thinking, Interview Analysis
<i>Partner NGO and Leaders</i>	Civil Rights; Community Engagement; STEM Education and Afterschool Program Development	Volunteer Coordination; Socioenvironmental Initiatives; Citizen Science Data Collection
<i>Community Members</i>	Survey respondents; Disaster Challenge Identification	Community Mapping Potential; Educational Program Participant;

(Comas Pagan, 2009), creating a vulnerability that was greatly exposed in the aftermath of Hurricane Maria and FEMA recovery efforts, which fell short of delivering an average of two million meals per day (Garcia-Lopez, 2018; Wolffe, 2017). Additionally, the Jones Act requires all cargo to be on U.S. ships when traveling between U.S. ports, obstructing incoming aid from other countries and further necessitating a reliance on U.S. intervention in archipelagic recovery efforts (Ora Bannan, 2020; Papavizas & Shapiro, 2018). In this sense, disaster recovery is similarly embedded in processes of debt restructuring, austerity, and colonialism, highlighting the immense importance of supporting redundancy in local disaster recovery, especially at the community level.

It is within this context of compounding disaster that we engage in a transdisciplinary collaboration. Our local partner, Caras con Causa, is an NGO founded in 2004, based in the Juana Matos community of Cataño, located in the western reaches of the San Juan metropolitan area. Caras con Causa specializes in STEM education and community development through after-school programs engaged in citizen science. Caras con Causa's leaders and educators recruit local schoolteachers and students to participate in afterschool activities, learning about socio-environmental sciences and collecting data related to water, mangrove cultivation, and wildlife identification, among others. To date, they have served several neighborhoods in the region by recruiting hundreds of students (ranging from kindergarten to post-secondary), teachers, and community members to actively participate in data collection.

4. Methods

Our virtual, transdisciplinary team set out to engage in a collaborative project that would meet the Caras Con Causa and the wider community within their current efforts and work to build “forward” towards more disaster-resilient futures. To briefly outline our approaches and methods, we begin this section with insight into our team formation. Next, we describe our co-production methodology. Lastly, we detail the post-engagement reflections intended to reflect on the successes and shortcomings of collaboration. The timing of this endeavor has been opportune as we have recently undergone a global shift to highly virtual arrangements, due to COVID-19, and therefore, key lessons learned can offer an early analysis of successes and areas for improvement in virtual collaboration.

4.1. Transdisciplinary team formation

Graduate students from diverse disciplines were recruited from universities across the United States to participate in virtual transdisciplinary research to address grand challenge scale problems under the purview of National Science Foundation (NSF) projects (#1639340 and 1833225) for Innovations at the Nexus of Food, Energy, and Water Systems Educational Resources (INFEWS-ER). From these candidates, a team with diverse research interests and skillsets was selected for a transdisciplinary study of Disaster Relief and Resiliency in Puerto Rico (Table 1). The collaborative and virtual nature undertaken by our team was initiated by this INFEWS-ER cohort challenge structure. It is important to note that at the start of this collaboration, Puerto Rico had

yet to experience the 2020 earthquake swarm and the COVID-19 pandemic had yet to receive global attention. This temporal detail affirms that the present methods undertaken at the time were opportunistic and novel, and the project collaboration occurred within a period of compounding disasters.

4.2. Co-production

Throughout this cohort challenge, our team engaged in a virtual collaboration with local stakeholders to co-create a process by which researchers and community members could co-produce work that support local, autonomous initiatives. Co-production is an iterative approach which frontlines collaborative decision-making and knowledge production in researcher-community teams (Lemos et al., 2018). What co-production looks like is vast and varied, and as such there is no set methodology (Hickey 2018; Filipe et al., 2017; Izumi et al., 2019; Mach et al., 2020). We describe our method of co-production below.

Coproduction consisted of four iterative stages: 1) Initial exploration and team formation, 2) Preliminary design, 3) Prototyping, and 4) Reflection (Fig. 3). Though not inspired by participatory design, these stages share a semblance to such practices (Spinuzzi, 2005). Our collaborators, Caras con Causa, participated in group calls at critical points in the design process, including idea-sharing, key updates (e.g., completed work), and pivotal discussions such as the working assumptions regarding Caras con Causa's present situation and needs. We began with brief introductions and discussions to identify what the ultimate goals of Caras con Causa were, which initiatives were ongoing, and what sorts of data might be of utility for the community. These discussions were followed by weekly brainstorming sessions via Zoom and systems process diagrams using Plectica (Cabrera & Cabrera, 2019), while documents were managed through digital repositories (Nithya & Selvi, 2017). Ideas were introduced through presentations which would be followed by structured discussions where the team shared feedback, learned from one another, discussed new directions, and considered possible implementation issues of the current design. Once the project design was mutually green-lighted by researchers and Caras Con Causa, we proceeded to the prototyping stage.

As Caras Con Causa was already coordinating a citizen science program containing geo-spatial data, our prototyping stage was modeled after a participatory mapping methodology, which reflects local knowledge and priorities (Corbett, 2009). For this work, we 1) collected and consolidated geo-spatial data, 2) constructed sample maps, 3) presented on and received feedback, and 4) implemented feedback. We engaged in a separate discussion with Caras Con Causa concerning current mapping and data capacity to ensure context-appropriate tools (Brown & Kyttä 2018). Different programs such as Google Maps, ArcGIS Online (Web version 2.16), and R (Version 3.5.1), were then assessed for data adaptability, user interface accessibility, visual appeal, and their potential for future community utility. Afterwards, the aforementioned software were utilized by the team to produce various sample resources (see Appendix). The resulting content was deliberated with Caras Con Causa to identify advantages and challenges (e.g., discrepancies, legibility, utility). This discussion was followed by a series of prototype

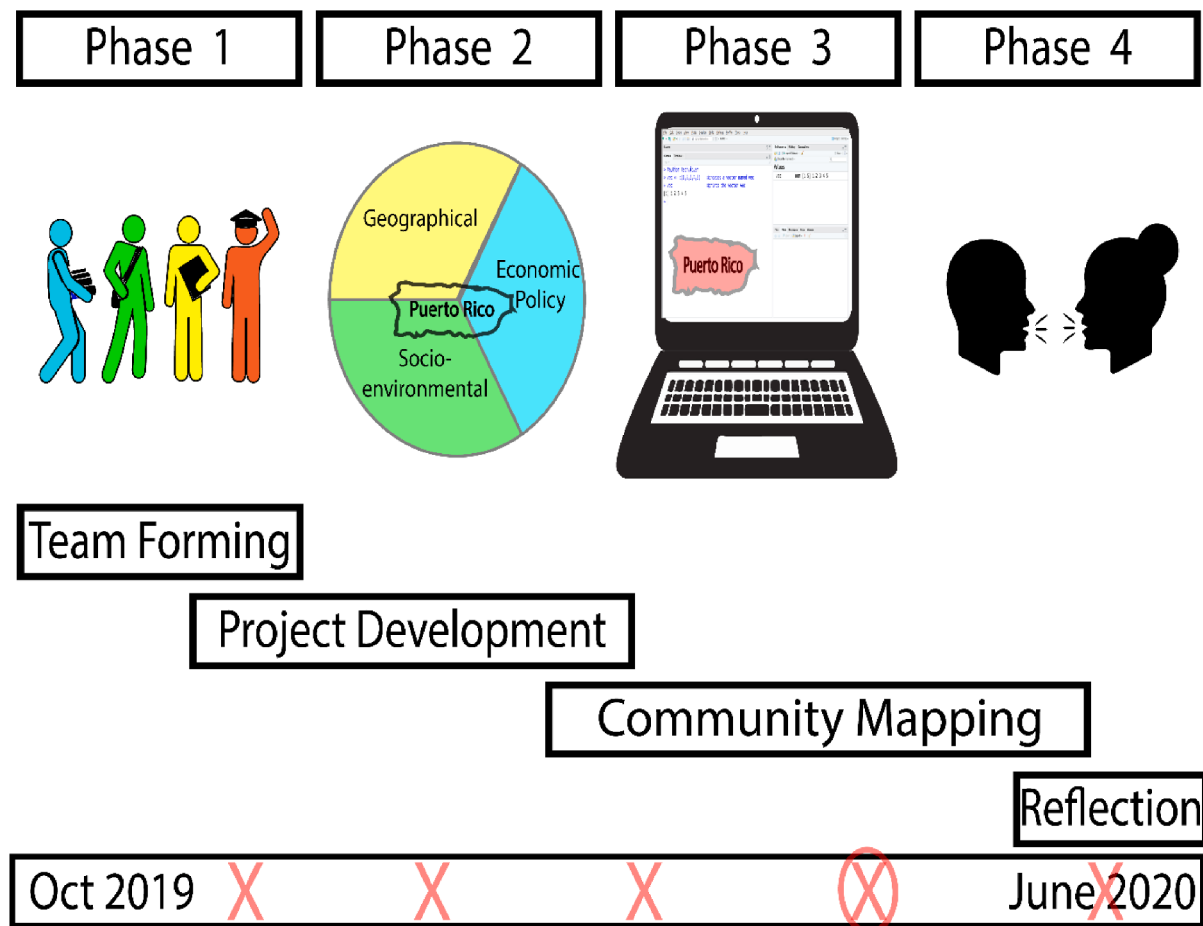


Fig. 3. Transdisciplinary project timeline broken down into phases. Red Xs on the timeline indicate focused stakeholder discussions, where the circled X was conclusion of the INFEWS-ER cohort challenge, which culminated in an online presentation deliverable. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

updates intended to incorporate partner feedback. As co-production is only as effective as the participatory process (Corbett, 2009), post-engagement reflections were conducted for feedback on how to improve the overall process and framework.

4.3. Post-Engagement reflections

Reflections with stakeholders can offer unique insights into the human dimension of disaster, expanding understanding of the knowledge, perspectives, values, and decisions for co-production (Martinez et al., 2018). Upon completion of the project and conclusion of the cohort challenge under the NSF INFEWS-ER program, post engagement reflections were performed and further analyzed for determination of best practices. Such reflexive research focused on stakeholders' perspectives and experiences can improve understanding of different socioeconomic, geopolitical, and disaster relief engineering and result in more constructive outcomes (Hjortso et al., 2005).

The reflection process began with a written portion, where the interlocutors were given a series of questions asking for their reflections, in either Spanish or English, according to their preference. Questions included defining important research terms (e.g., disaster, resilience), their opinions on project outcomes, and recommendations for similar-type groups moving forward. Phase two of the reflection process included recorded, virtual discussions to discuss the written answers and provide a space for follow-up questions. Semi-structured reflections were conducted with the same respondents in a discussion format to allow for clarification and elaboration from the written responses. These discussions were attended by all academic members of the project team,

and discussion was moderated by a group advisor. During the discussions, the rest of the team utilized Google Docs to develop follow up questions in real-time and inform the moderator of directions to take the discussion. Two discussion sessions were conducted with different Caras con Causa representatives, one including the organization executive director, and the other including two program leaders. All sessions were conducted in English.

5. Results and discussion

The primary result of our collaboration was the development of an iterative framework to guide virtual, transdisciplinary collaborations for disaster relief and resiliency within the context of autonomous community responses (Fig. 4). Recent disaster risk reduction research illustrates a limited use of local knowledge and calls for the creation of collaborative processes which value and meaningfully integrate local knowledge in risk reduction practices (Trogrlić et al., 2021). Moreover, initiatives which emerge from within and are led by communities are more likely to be trusted, engaged, and sustained over time (Kirkby et al., 2018; Sherman & Ford, 2014). The present work built on Caras Con Causa's autonomous responses to engage in and establish a co-production process that integrates local and external scientific knowledge for strengthening community disaster resilience and recovery initiatives. As post-project reflections between case-study partners remain rare (Lux et al., 2019), the reflections from Caras con Causa representatives are interspersed throughout, providing key insights into the co-developed process framework illustrated in Fig. 4.

A key aim of this overall project was to provide a tool through which

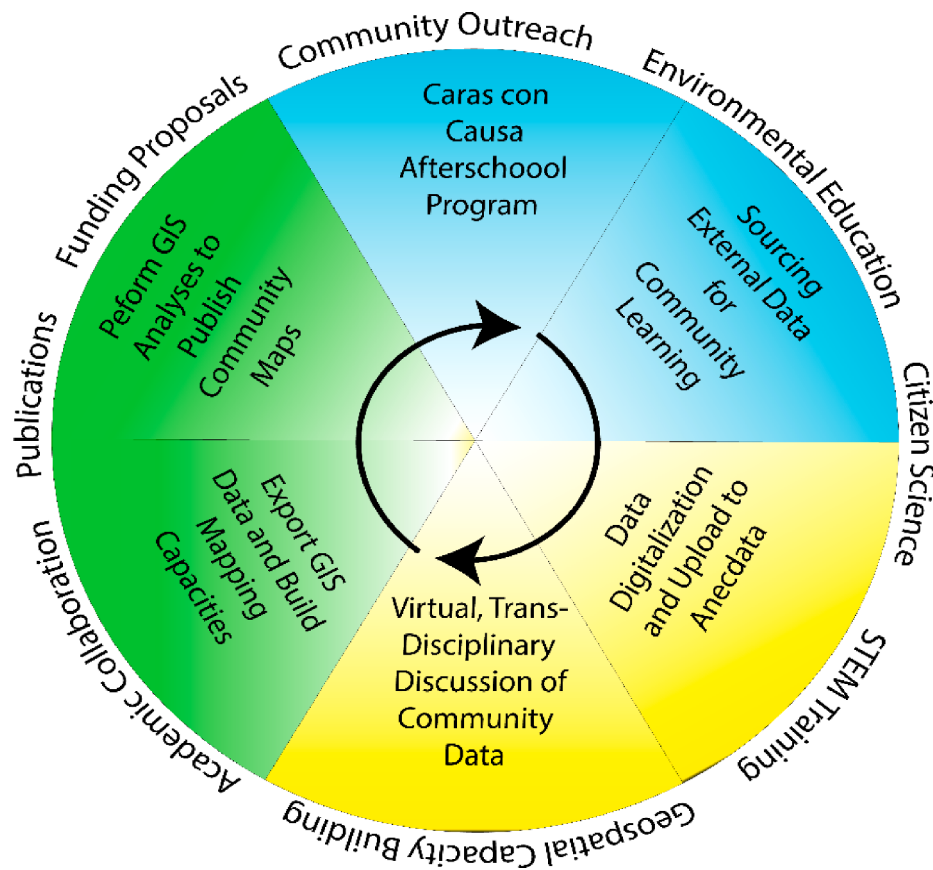


Fig. 4. A depiction of the team process (inner circle text) as related to the general process steps and the associated outcomes for disaster relief and resiliency in communities (outer circle text).

Table 2

Comparison of mapping platforms discussed in stakeholder meetings on community mapping in virtual, transdisciplinary collaboration.

Mapping Platform (Package, if applicable)	Advantage(s)	Disadvantage(s)	Anticipated Outcomes
Google My Maps	• Free • Simple and accessible to all • Collaborative potential • Easy dissemination	• Lacks technical analysis and settings to enhance maps	• Can generate real time maps for communities during/after disasters
R (Leaflet)	• Free • Numerous mapping packages and settings • Serves many purposes (e.g., statistical analysis, map generation) • Collaborative potential • Possibilities for easy dissemination	• Requires programming knowledge	• Generates data analysis and programming experience • Potential for producing high-quality maps
ArcGIS Online	• Numerous mapping functions • Allows for technical analysis • Directly compatible with storymap • Collaborative potential	• Requires expensive subscription • Requires instruction	• Ability to process and analyze geospatial data • Potential for producing high-quality maps

decision-making capacities can be heightened (Walter et al., 2007) and provide a potential pathway towards accomplishing other goals. Throughout meetings with Caras Con Causa, they shared obstacles they have experienced, such as efficiently uploading and using their collected data, having limited resources to obtain funding, and limited capacity to use advanced mapping software. Caras con Causa are not alone, as these barriers are heavily cited in the climate services literature (Daniels et al., 2020). Additionally, Caras con Causa shared multiple goals, including expanding their educational outreach to adult populations, standardizing and consolidating their data, and increasing their ability to apply for new and diverse funding sources. These goals were accounted for in the broader co-production process. Specific activities in each slice of the

inner circle in Fig. 4 represent steps in the overall color-coded process while the outer ring corresponds to broader impacts that can be achieved through their successful implementation. As funding agencies are increasingly calling for the incorporation of knowledge co-production (Arnott & Lemos, 2021), the co-designed process not only functions as a means through which diverse data can be made legible for DRR efforts but also serves as a structure to facilitate goals such as increased grantsmanship.

To elaborate more specifically, we began with community and field data gathering (blue) where our team consolidated local, gubernatorial, and federal open-access geospatial data for Puerto Rico alongside data from Caras con Causa (e.g., student recruitment, citizen science data).

Where scientists face critical knowledge gaps, communities must often overcome information deficiencies due to lack of access, capacity, or resources (Liu et al., 2018), making such data integration critical to co-production and especially for disaster relief and resiliency. Moreover, given that community members often exchange knowledge through interpersonal communication and social networks (Johnson et al., 2014), connecting this process to citizen science provides a gateway to knowledge dissemination which is particularly useful for disaster preparedness. Next, moving to data organization and analysis (yellow), our transdisciplinary team discussed the limitations and possibilities within the consolidated dataset, as well as the advantages and disadvantages of potential mapping software (Table 2). Such dialogues are part and parcel of successful transdisciplinary projects, not only creating an environment conducive to deliberation and negotiation but also ensuring appropriate solutions are promoted over lesser ones (Pischke et al., 2019; He, 2019).

Finally, with input from our stakeholders, we shifted towards the prototype stage (green), which led to the creation of several end-products. These include: (1) visualizations produced in Google 'My Maps' and ArcGIS (Web version 2.16), (2) an interactive map produced with R (Version 3.5.1), (3) a bookdown that provides instructions for making useful community mapping tools, and (4) a live, online storymap for publishing and showcasing project updates (see [Supplementary](#)). These tools are designed to illustrate key features that may be useful to know when developing disaster preparedness plans and help target areas where NGOs could expand their community outreach network and operations by leveraging existing social capital (Roque et al., 2020). For example, Caras con Causa's student recruitment data overlain atop geospatial layers depicting flood zones and social vulnerability may assist with area prioritization in disaster planning. Furthermore, such final products are particularly vital considering that too often communities working with research teams experience extractive collaborations without seeing any returns (Wilmsen, 2008; Zinn, 1979). Although similar to Daniels et al. (2020) in its process-centric approach to co-production, we retain the focus on products and outputs, seeing this as an invaluable asset to both co-production and healthy relationship building between academics and partner communities.

The detailed co-production methods and example products created throughout our virtual, transdisciplinary collaboration are a novel outcome that offers stakeholders direct pathways to increased capacity in DRR decision-making. These approaches "better allow the organization to select and plan what projects they try to implement vs ones they wait for the teams to carry out, so that time and resources are used more efficiently." (Written Response - Executive Director). Indeed, grassroots organizations are doing incredible work to address disaster relief and resilience in Puerto Rico (Fitzpatrick & Molloy, 2014; Ortiz Torres, 2020; Roque et al., 2021; Krantz, 2020), yet they often find themselves short of resources. This dynamic presents a critical juncture where transdisciplinary teams can form in support of emergent responses, and specifically an area to which this work contributes. As this research was conducted in a strictly online environment, the process and reflections offer novel, though complementary, insights to "best practices" recently published in the co-production literature (Karrasch et al., 2022; Pohl et al., 2021; Lux et al., 2019; Daniels et al., 2020). While future studies are needed to determine the impact(s) of our proposed process (Walter et al., 2007; Lux et al., 2019), we outline critical advantages, challenges and lessons learned for other virtual, transdisciplinary teams seeking to build on autonomous disaster responses.

5.1. Advantages

While traditional face to face methods can offer greater social presence for enhanced communication and trust (Olson & Olson, 2000), virtual collaborations can make interactions more accessible to stakeholders, increasing their frequency and reducing costs when subject to distance, and thus improve the outcome and benefits recurring

interactions (Bergiel et al., 2008; Jost et al., 2021). Moreover, while investigating the role of knowledge sharing and trust in virtual collaborations, Alsharo et al. (2017) find that knowledge sharing fosters trust in virtual collaborations. One representative (SH Reflection - Volunteer Coordinator: 1:14:30) specifically discussed knowledge and resource sharing: "for example, there is a documentary [Vietnam, Puerto Rico] on one of the efforts of the communities that were fighting illegal expropriation and the organization helped them through that process... that would be a cool thing for you guys to watch so you have a more personal connection." The film provides insight into the area's long history of community organizing and their success in the fight against injustices. In this sense, Caras con Causa shared resources which enhanced mutual learning. Mutual learning throughout co-production is key as it establishes the foundation for feedback loops that have proven valuable in both transdisciplinary research (Lotrecchiano, 2010; Pohl et al., 2021) and disaster resilience (Kim and Zakour, 2017). Indeed, research suggests that as ties grow stronger within collaborative groups, so too does the knowledge creation process (Wang, 2016). In this vein, Caras con Causa indicated that they could produce video "tours" to connect us with their specific work. Likewise, and in the spirit of reciprocity, it was recommended that the researchers "prepare something to help us know you [virtual collaborators] better and make the distance experience more personal" (SH Reflection - Project Coordinator: 55:27). Ultimately, our collaboration demonstrates virtual connection can establish a foundation which allows for "the capacity to delve more into the issues" (SH Reflection - Volunteer Coordinator: 52:10).

"Effective participatory processes not only have the potential to strengthen local autonomy but are also likely to result in adaptation actions that are suitable to the local context and congruent with local worldviews, beliefs, values and aspirations" (Kirkby et al., 2018; Chambers, 1997; Reid et al., 2009). This notion was confirmed when discussing the prototype and sample products [SI Reflection - Executive Director: 55:20], as the stakeholders stated that these resources taught them a different way to visualize their outreach, educate the public about their work and impact, and improve awareness about key environmental assets. This was a particularly exciting outcome, hinting at the process' impact, and can be thought of as expanding their "inventory of possibilities", or what they consider possible (Marino et al., 2022). To this effect, they also acknowledged the critical role of NGOs in translating the community needs to collaborators because of their nuanced understanding and intimate relationships with community members. They likened their ability to understand the community and provide innovation on their behalf to Henry Ford's ability to translate community needs for bigger or faster horses into a car. The key role of NGOs in disaster relief and resiliency is long supported in the literature (Fitzpatrick & Molloy, 2014; Lassa, 2018), and in building on autonomous efforts, this work both affirms and advances the important role that NGOs like Caras con Causa play in community disaster relief and resilience.

5.2. Challenges

Transdisciplinary teams are well suited to address complex problems (Rodríguez et al., 2019), yet they are not without challenges. Although remote teams have greater potential to combine geographically dispersed experts, communities, and stakeholders in order to amplify the effects of transdisciplinary efforts (Rodríguez et al., 2019), the online environment can place disaster at a psychological distance, or outside of a person's direct reality (Liberman et al., 2007). This has repercussions for how outsiders perceive and approach disaster(s). In a 2015 study of disaster terminology, "the most consistent definition for disaster appeared to be 'the widespread disruption and damage to a community that exceeds its ability to cope and overwhelms its resources'" (Mayner & Arbon, 2015). Although scholars suggest that the definition of disaster needs to be streamlined (Mayner & Arbon, 2015; Staupé-Delgado, 2019), the most widely utilized definition of disaster centers

Table 3

Key topics and perspectives from stakeholder reflection analysis in Post-Engagement Reflections.

Topic	Definition/Perspective	Stakeholder (SH) Reflection, timestamp
Disaster	<i>Disaster can be defined in various ways according to different disciplines, but in general they are both physical and social processes. In a practical sense, disaster is difficult to define until it has been experienced.</i>	SH Reflection - Volunteer Coordinator: 12:43; SH Reflection - Project Coordinator: 15:03; SH Reflection - Volunteer Coordinator: 19:37 (SH Written Answer Executive Director)
Immersion and Community Interactions	<i>Maintain the local community as the primary focus, and all efforts to conduct research should be done in tandem with a local group that can advocate for the needs and priorities of the community and provide vital contextual knowledge.</i>	SH Reflection - Volunteer Coordinator: 1:14:30
Transdisciplinary Team Onboarding	<i>The nature of transdisciplinary teams is that members have diverse skill sets and backgrounds, so it is simultaneously important to understand the backgrounds of others, seek out the expertise of others, and communicate your own expertise in a way that is accessible to all other team members.</i>	SH Reflection - Project Coordinator: 1:01:13; SH Reflection - Volunteer Coordinator: 1:00:04
Virtual Interactions and Communication	<i>Virtual interactions can make communication very efficient; however, it is important to keep all parties updated and send preparatory materials before meetings.</i>	SH Reflection - Volunteer Coordinator: 59:09; SH Reflection - Volunteer Coordinator: 59:30; SH Reflection - Volunteer Coordinator: 1:00:18; SH Reflection - Project Coordinator: 1:01:49; SH Reflection - Project Coordinator: 55:27; SH Reflection - Volunteer Coordinator: 52:10
Project Outcomes	<i>This project was effective in both outlining tools and processes for effective transdisciplinary research and in creating online mapping methods to be turned over to the organization and implemented further</i>	SH Reflection - Executive Director: 43:07 (SH Reflection Executive Director-'Storyboards')

community, suggesting an inherently situated definition. The iterative discussions between our team of researchers and local stakeholders facilitated the co-production of important definitions to guide our collaborative, transdisciplinary process (Table 3). Thus, we contend that a narrowed and pre-established definition of disaster in co-production research can be counterproductive, as it risks minimizing local understandings. “It is an easy definition to look up in Google, but when you experience it, it’s different” (SH Reflection - Volunteer Coordinator: 12:43). Through discussion with Caras con Causa, it became apparent when looking at disasters in Puerto Rico, one must factor in aspects like PROMESA, because “while these are not natural disasters, they definitely have had a toll on us and our capacity to rebound.” (Written Response - Executive Director). Such contextual blind spots, or perspectival differences, are common in transdisciplinary research but they can and should be overcome (Rodríguez et al., 2019). As a cohort, we recognize that nothing can adequately substitute for in-person, on-the-ground engagement; however, this may not always be possible, heightening the need for reflexive conversations. Multiple transdisciplinary approaches implementing education, training, and field practice have been tested by researchers working with local communities to bolster DRR, concluding that iterative discussion between disciplines and stakeholders results in the best outcomes (Matsuura & Razak, 2019). In other words, “everything needs to be put into context... whatever expectations we set... will be grounded in that context” (SH Reflection - Executive Director: 43:07).

Similarly, there was an emphasis on educating outside collaborators about the existing capital and skills present in the community. They noted the importance of partnering with a local organization to enhance a team’s ability to be contextually appropriate, utilize existing resources, and respect relevant community needs; however, external researchers simultaneously must be acutely aware of community priorities and reduce the project footprint, in terms of required investment (e.g., resources, time). The challenge of resource barriers, such as the ones presented here (e.g., time constraints, project footprint), is commonly noted in the community-based adaptation literature (Piggott-McKellar et al., 2019), and they are only heightened in virtual settings which demand more time and energy (Platt, 1999; Nemiro et al., 2008). This challenge is further exacerbated by team membership attrition and the associated effects (e.g., loss of critical expertise, slows in momentum), which are common among transdisciplinary teams (Norris et al., 2016), including our own. This presents a paradox as participatory projects call for more inclusive practices. Methods such as workshops, focus groups, dialogue sessions, scenario-work, and deliberative polling increase participation leading to more effective outcomes, yet can also be time

consuming and when coupled with academic timelines such processes can place undue burdens on partner organizations or stakeholders (Galende-Sánchez & Sorman, 2021; Thompson et al., 2017; Marino et al., 2022).

Given the challenges associated with project footprints in virtual, transdisciplinary, and participatory projects, Caras con Causa called for increased awareness from university groups working on collaborative projects to see past the scholarly research and identify only the relevant information to be communicated. Although good practices are addressed, co-production literature often fails to account for the politics and power relations driving complex issues like time commitments in co-production endeavors (Turnhout et al., 2020). The dynamics reflected here bring power to the fore of the co-production process and illustrate a pivotal entry point to begin addressing unequal power dynamics within the co-production process. Caras con Causa’s reflections identified a need to establish roles and manage expectations on both sides of the partnership at the beginning and throughout the project, suggesting that participatory paradoxes might be mitigated via recurring discussions which center care and project flexibility. (Lang et al., 2012; Norström et al., 2020). To this effect, collaborative work balance cannot be pre-determined even if co-designed, but rather must be iteratively evaluated throughout a project.

5.3. Lessons learned

It can be difficult to assess community needs and how they evolve in complex disaster circumstances, especially years after they occur and with additional events heightening on the ground situations. While we have discussed our co-production process in detail, we present a broadened overview for wider application (Fig. 5). There are three generalizable steps in the transdisciplinary process that are depicted here as ‘community and field data gathering’ (blue), ‘data organization and analysis’ (yellow), and ‘tool generation and prototyping’ (green), and we elaborate how they both transition from one to another (arrows) and are centered around target outcomes (inner triangle). The illustration represents critical phases for integrating transdisciplinary and co-production frameworks generally (Pohl et al., 2021) and disaster resilience specifically (Daniels et al., 2020), similarly demonstrated through previous case studies and frameworks (Karrasch et al., 2022). Going forward, transdisciplinary disaster research should emphasize deep contextuality and mutual benefits between external researchers and local stakeholders to enable more timely and appropriate responses (Lux et al., 2019). Lessons learned from this virtual co-production process, shared below, can aid future teams in developing similar projects for

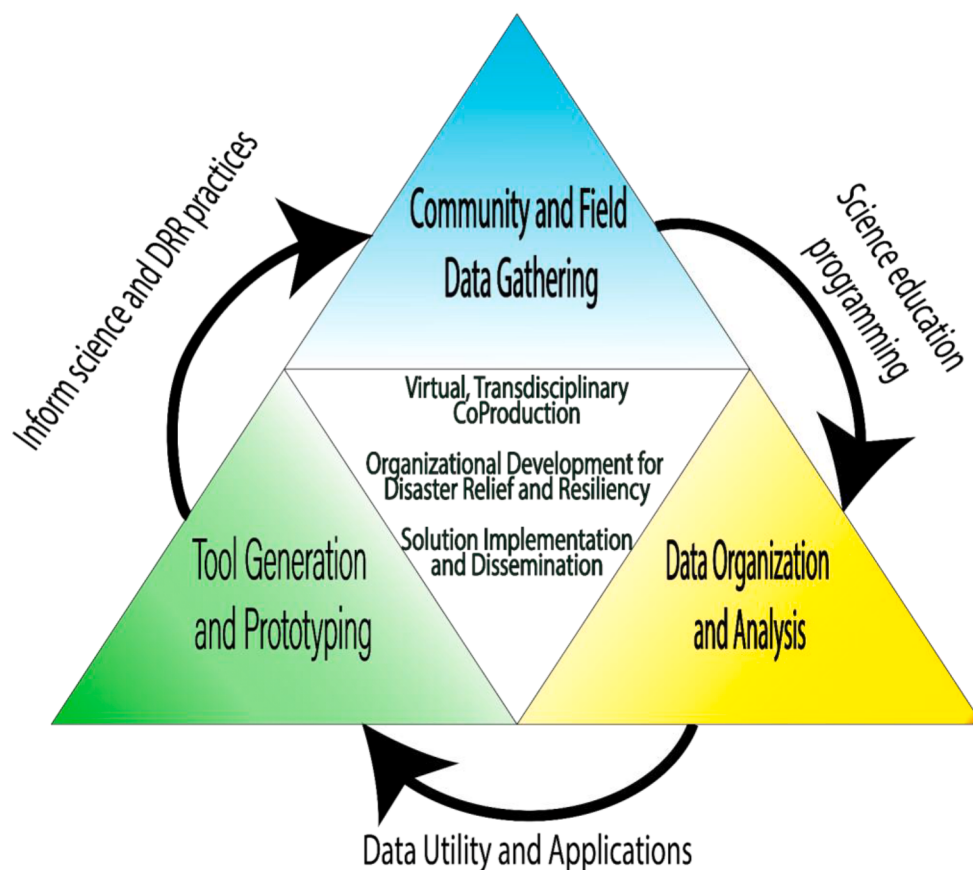


Fig. 5. General process model by which data is collected, analyzed, and visualized for dissemination to build local, scientific, and transdisciplinary capacities for disaster relief and resiliency in communities.

Table 4
Challenges, Advantages, and Lessons Learned from the Virtual, Transdisciplinary Project.

Challenges	• Defining terms for project to relate disciplines • Team retention in virtual settings to minimize discontinuity • Lost opportunities for in-person collaboration (COVID-19)
Advantages	• Diverse knowledge background • Direct community participation through collaborator insights and program
Lessons Learned	• Need for establishing and underscoring leadership roles • Consideration for community time, patience, and health are integral to successful project outcomes • Incorporate opportunities to build relationships (Example: Vietnam documentary Watch Party)

DRR capacity-building alongside autonomous responses.

First and foremost, co-production in DRR requires shedding pre-conceived notions of disaster and, instead, entering into a mutual understanding of the disaster(s) in context (Table 4). Such definitions must be co-produced because individual perspectives may be fragmentary. For example, our partners asserted that disasters are dependent on “inter-connected systems” and recovery depends on more than “focus [ing] on one piece” of the systemic puzzle (SH Reflection - Volunteer Coordinator: 19:37). Second, virtual DRR co-production needs to deeply invest care and awareness into team introductions and interactions. For instance, in future collaborations of this nature, teams should be intentional about learning the background of each collaborator and keep that in mind when communicating. In their reflection, one collaborator stated “I’m not an expert in some of these topics. So, maybe it would be good to know the background of the person you’re working with” (SH Reflection- Volunteer Coordinator: 1:00:04). These sentiments can arise

when certain representatives or important team members are unavailable and delay communication, where others are needed to relay key information to directors for decision-making. Some Caras con Causa members reflected that it would be “a little bit easier if some things were broken down a little bit simpler for me so when I relay the message... I can make sense of what I was saying.” (SH Reflection - Volunteer Coordinator: 1:00:18). This also brings to the forefront the active need to diminish scientific jargon and complex, lengthy explanations in such co-production processes. A practical suggestion offered was to provide collaborators with updated project onboarding summaries. Our local partners affirmed that “we need to get more information about the purpose of the group, from where you come, and your expertise, because this way we can be more prepared” (SH Reflection - Project Coordinator: 1:01:13). Lastly, when setting expectations, it is important to account for and offset any potential burdens resulting from the collaboration (Arnott et al., 2020a; Dewulf et al., 2020; Latulippe and Klenk, 2020). These expectations must be returned to and adjusted iteratively.

6. Conclusions

Applied transdisciplinary studies should center local contexts and communities when approaching DRR. This virtual research makes novel contributions to DRR, where transdisciplinary co-produced projects are scant (Gall et al., 2015). In summary, the INFEWS-ER initiative aimed to virtually connect emerging scholars from universities across the United States with a grassroots organization in Puerto Rico to collaboratively build on autonomous responses to the compounding effects of multiple disasters. The co-production process should be centered on iterative engagements with local stakeholders designed to pair organization and community needs with scholar knowledge and skills. The resulting process creates participatory pathways for bolstering decision-making

capacities and complementing autonomous responses to disaster events. In addition to outlining the co-produced process, this paper details post-engagement reflections which resulted in critical insights and lessons learned. While this project specifically engages autonomous responses for disasters in Puerto Rico, the broader impacts lay groundwork for virtual, transdisciplinary collaborations to support and build sustainable solutions to complex challenges alongside communities who are directly impacted by such solutions. Future research should further measure the impact of this process framework, its outcomes, and its efficacy for facilitating preparedness and recovery from disasters (Hansson and Polk, 2018; Durose et al., 2018).

Author Contributions

The National Science Foundation (NSF) Innovations at the Nexus of Food, Energy, and Water Systems Education Resources (INFEWS-ER) project recruited, organized, and supervised team formation and development over the original project span between October 2019–March 2020. All graduate scholars were originally participants in Disaster Relief and Resilience Cohort Challenge. Michael Stablein led and organized the team in conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing the original draft, and reviewing and editing. Jesann Gonzalez Cruz contributed to conceptualization, formal analysis, investigation, methodology, visualization, writing the original draft, and reviewing and editing. Emine Fidan contributed to conceptualization, data curation, formal analysis, investigation, methodology, software, visualization, writing the original draft, and reviewing and editing. Samuel Reed contributed to conceptualization, data curation, formal analysis, investigation, methodology, writing the original draft, and reviewing and editing. Jessica Talbot contributed to conceptualization, data curation, formal analysis, methodology, writing the original draft, and reviewing and editing. Riveraine Walters contributed to conceptualization, data curation, formal analysis, methodology, writing the original draft, and reviewing and editing. Ayorinde Ogunyiola contributed to conceptualization, data curation, formal analysis methodology, software, visualization, writing the original draft, and reviewing and editing. Michael Fernandez Frey, Mariela Ramírez, and Belen Rosado Casanova all work for Caras con Causa and contributed to conceptualization, formal analysis, methodology, and reviewing and editing. Luis F. Rodríguez, Anna-Maria Marshall, and Jill Heemstra provided mentorship and leadership to the cohort challenge participants as project advisors, thus contributing conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing the original draft, and reviewing and 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloenvcha.2022.102558>.

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