

Challenges and opportunities in building community-driven adaptive capacity under climate change for smallholder farmers in the Global South

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Abstract

Purpose – This study responded to the disproportionate impacts of climate extremes on smallholder farmers in the Global South by developing frugal innovation tools and strategies to support climate resilience and agricultural decision-making through community-academic partnerships.

Design/methodology/approach – Using a community-based participatory approach, academic researchers collaborated with a local development organization and stakeholders through remote focus groups and surveys to co-develop the NicaAgua mobile app. Designed for areas with limited internet connectivity and digital



literacy, the app integrates real-time weather data, short- and long-term forecasts and historical climate trends, with user-friendly visuals and interpretive guidance.

Findings – Frugal innovation and community engagement identified six key functionalities prioritized by users: short and seasonal forecasts, early warnings, local weather station data, climate change metrics and the moon phase. The app showed moderate to high forecasting skill at local scales. Community feedback confirmed the need for accessible forecast tools tailored to local indicators, while also revealing barriers such as low digital literacy and internet access. Despite widespread smartphone ownership, older adults and women often faced challenges in app use, requiring inclusive design strategies.

Originality/value – This study presents a frugal, community-driven approach to localizing global climate science for vulnerable farming communities. It highlights effective strategies for designing equitable, accessible digital tools to support climate adaptation, offers lessons on fostering transboundary academic-community collaboration and contributes to building smallholder farmers' capacity to manage climate risks in Central America.

Keywords Central America, Climate change, Capacity building, Mobile application, Agricultural decision-making, Climate forecasting

Paper type Research paper

1. Introduction

Climate disruption from anthropogenic causes already affects every corner of the planet, albeit in different ways and to varying degrees (IPCC, 2023; Rezaei *et al.*, 2023). Changes for a number of climate change indicators, such as air temperature warming, extreme weather events and glacial melting, have far exceeded model projections (Allan *et al.*, 2023; Lee *et al.*, 2021). As a result, vulnerable communities are experiencing the increasing effects of climate disruption and are facing an urgent need for local adaptation (Abbass *et al.*, 2022; Reyes-García *et al.*, 2024).

One of the major political discourses surrounding climate change policy has been what constitutes climate justice in a rapidly changing world and how to devise policies and strategies to implement it (Newell *et al.*, 2021). The principles of climate justice recognize that historically marginalized and vulnerable populations are disproportionately affected by the impacts of climate change, such as excessive heat, drought, floods, loss of snow and water resources, ecological changes and disruptions of the agricultural calendar (Newell *et al.*, 2021; Dorkenoo *et al.*, 2022), thus climate justice advocates for equitable distribution of both the burdens of climate change and the efforts to mitigate it. To meet this challenge, climate justice theorists, governments of the most vulnerable nations and activists and organizations in both local and global civil society have articulated a range of frameworks for understanding the relationship between the effects of climate change and conceptions of justice and fairness (e.g. Schlosberg, 2012; Schlosberg and Collins, 2014; Newell *et al.*, 2021). These approaches include seemingly straightforward “polluter pays” models (based on historical responsibility), “fair share” models (based on the equal allocation of emissions) and various “rights-based models” (such as development rights, human rights and environmental rights). The strong assumption behind these models is that normative theories of climate justice can ground global climate policies, which to date has proven elusive.

As the global political will to slow anthropogenic climate disruption has been insufficient, practical approaches to local adaptation are increasingly important, though the willingness to absorb adaptation costs by developed countries and responsible industries has fallen significantly short of need (Lee *et al.*, 2021). This leaves a crucial dimension under-addressed: how justice can be furthered from the bottom up, by communities adapting to the growing effects of climate change on the ground, leveraging frugal innovation and community academic partnerships (Prabhu, 2017; Rosca *et al.*, 2018). While much of the academic discussion on climate justice centers on ideal theories of justice or the policy

approaches favored by prominent environmental NGOs, a separate and distinctive discourse has emerged from grassroots movements (Schlosberg and Collins, 2014; Westoby *et al.*, 2021). These consistently reflect the core principles of environmental justice, emphasizing the lived experiences of local communities, unequal vulnerabilities to climate impacts and the call for local autonomy and resilience. An important question in this context is how those can be applied to the reality and necessity in less developed yet highly impacted regions, such as rural areas of Central America. Our study seeks to contribute to this discourse by examining the challenges and opportunities in building community-driven adaptive capacity under climate change for smallholder farmers in northern Nicaragua through a climate adaptation app developed through a community–academic trans-border partnership.

As a region long identified as a climate change hotspot (Giorgi, 2006), many parts of Central America have experienced warming and associated impacts over recent decades (Anderson *et al.*, 2019; Alfaro-Córdoba *et al.*, 2020; Cavazos *et al.*, 2020; Stewart *et al.*, 2022). While changes in precipitation have been more variable (Hannah *et al.*, 2017; Hidalgo *et al.*, 2013), drought frequency and more arid conditions during the time of boreal summer (June–August, JJA) have seen significant increases (Stewart *et al.*, 2022), which can disrupt critical crop cycles and contribute to food insecurity (e.g. Mekonnen *et al.*, 2021). This is especially critical in the Central American Dry Corridor (CADC) (Gotlieb *et al.*, 2019; Stewart *et al.*, 2022), a more arid region with exceptional susceptibility to drought and its impacts. As the climate continues to warm through the 21st century, arid conditions are projected to intensify (Karmalkar *et al.*, 2011; Hidalgo *et al.*, 2013; Maurer *et al.*, 2017) and disproportionately impact already dry regions in the CADC.

The mid-summer drought (MSD) is a regional phenomenon dominant in many areas of Central America and in other areas. It partially overlaps with the CADC and is characterized by a bi-modal rainy season centered in boreal summer (June, July, August, JJA), the features of which drive the planning for one or two planting cycles by smallholder farmers and are difficult to anticipate. Recent studies have shown the MSD to be changing (Anderson *et al.*, 2019; Maurer *et al.*, 2022) and this is projected to become more extreme through the 21st century (Rauscher *et al.*, 2008; Maurer *et al.*, 2017).

Throughout Central America and the Global south, smallholder farmers substantially contribute to their nation's food supplies and economic activity, while simultaneously facing food and water insecurity and particular vulnerability to climatic changes (Donatti *et al.*, 2019; Alpizar *et al.*, 2020). In northern Nicaragua, economic development and the supply of basic needs infrastructure has been hampered by war and political instability (Fitzgerald, 2022), and there is high potential for climatic shifts (Stewart *et al.*, 2022).

An important way smallholder farmers can become more resilient to a dynamic, disrupted climate, is to build adaptive capacity on the community scale. Adaptive capacity describes the ability of a community to adjust to climate change, to reduce the likelihood of potential damages, to take advantage of opportunities or to cope with the negative impacts of climate-related hazards. The process of capacity building seeks to work with stakeholders to increase their knowledge, networks, skills and resources to adapt in a fast-changing world (Carmen *et al.*, 2022; Dayamba *et al.*, 2018). An important premise for this capacity building are reliable forecasts and relevant information that enable effective planning for and responses to extreme events. Our partner communities in the study area repeatedly expressed the need for such information and forecasts.

Several dynamic, statistical and hybrid forecasting approaches have been developed for Central or South America (i.e. Alfaro *et al.*, 2016; Sotelo *et al.*, 2020; Ordoñez *et al.*, 2022) to support the development of adaptive capacity. These approaches take advantage of various climate products to lessen risks. Use of these forecasts is dependent on the perception of skill

(Babcock *et al.*, 2016). Even given skillful forecasts, translating seasonal (or other) precipitation forecasts into a format that smallholder farmers can directly use involves overcoming several hurdles, including barriers to access available meteorological and other data sets held by public and private sectors, lack of completeness and accuracy for available meteorological data, delays in the transmission of meteorological data and information delivery such that the information is no longer timely and actionable, difficulty to understand and apply climate data by decision makers, including smallholder farmers, and a lack of skill for short-term and seasonal forecasts at the spatial scale and for the climatic variables needed by stakeholders. Overcoming these barriers includes providing not only accurate and complete forecast data but also processes that build trust and ensure farmers understand and use the data appropriately (Blumenthal *et al.*, 2014).

While seasonal forecasts are important decision support tools for protracted climatic phenomena such as drought, smallholder farming operations are also affected by short-term extreme weather events such as intense storms/rains, shifts in the beginning of the rainy season or the timing of the MSD. In addition, while mobile phone use is ubiquitous even in very rural areas of Central America, access to larger screens and interfaces tailored to their specific needs is much less common. In addition, crop models have not been designed to take local agricultural practices into account. Finally, no existing mobile application we found attempted to quantify, visualize and communicate climate change at a community level. We seek to address these gaps through a participatory action research partnership that has designed and developed a mobile app (*NicaAgua*) as an accessible tool to support capacity-building efforts of our partner organization in the study area. The app provides short-term and seasonal forecasts, information on local climatic shifts, locally relevant metrics, the capacity for early warning messages and measurements from a local weather station. Based on our work developing this frugal innovation tool, we seek to draw broader lessons on: How to leverage community-academic partnerships that cross the Global North/South divide for climate adaptation? How best to provide skillful and locally relevant short-term, seasonal and longer-term climate and climate change information in underserved regions such as Central America? and What strategies can make seasonal and short-term rainfall forecasts reliable and accessible in a way that supports building adaptive capacity? These questions are examined in the context of the challenges that smallholder farmers in Central America face regarding climate variability and change, and the capacity to respond to those changes.

2. Methods and data

2.1 Leveraging community–academic partnerships across the Global North/South divide

2.1.1 Community engagement. The development of the *NicaAgua* app and forecasts have grown out of a multi-year community-led engagement with a local development NGO, Social Development Association of Nicaragua (ASDENIC) in the Segovias region of northern Nicaragua (Figure 1). ASDENIC was founded in 1990 as a local development agency established by law and legal status granted by the National Assembly of the Republic of Nicaragua to promote social and economic development of rural communities and urban settlements, mainly in the region of Las Segovias in northern Nicaragua. The partnership between an academic institution in the USA and a community-based organization in Nicaragua that forms the basis for this study exemplifies a collaborative effort to bridge the Global North/South divide through equitable knowledge exchange and capacity building. Rooted in mutual respect and long-term engagement, the alliance aims to co-produce contextually grounded research that supports local priorities while enriching academic understanding. In 2018, despite the restrictions of the US Department of State to travel to Nicaragua due to an uncertain political situation, we were able to keep developing our

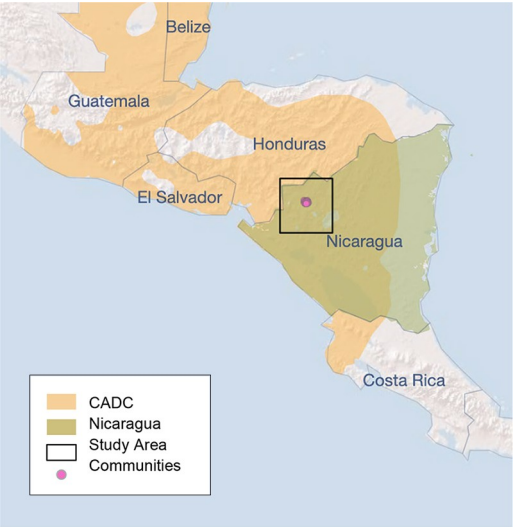
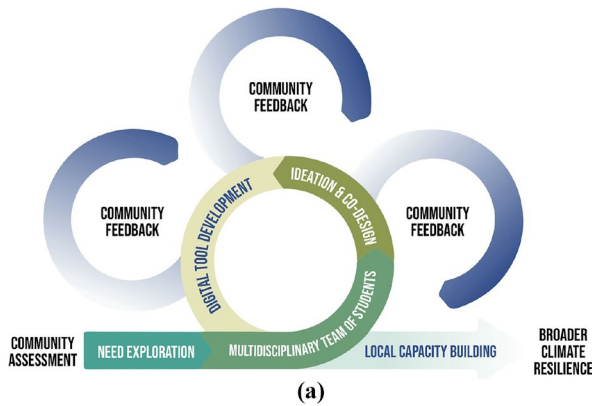


Figure 1. The study area within the Central American Dry Corridor (CADC)

project with ASDENIC, including our joint community activities, utilizing a remote participatory approach.

ASDENIC works with about 50 communities of approximately 600–1,200 people; 13 communities with which ASDENIC has longer and stronger relationships are the focus of this study. They are located in the CADC and rely on the rainfall patterns associated with the MSD to grow predominantly coffee for export and diversified crops for domestic sale and consumption. The most important economic activity in the region is rainfed agriculture. The communities are situated around an area of higher elevation which is the source of water capture for the villages. Small systems supply water from springs above the villages for a few hours each day, but water supplies vary in distinctly seasonal systems.

Our work has followed the principles of community-based participatory action research (CBPAR), a collaborative, participatory research approach that equitably involves community members, organizational representatives and researchers in all aspects of the research process. The goal is to remain grounded in the specific cultural and social context of the community and to combine knowledge with action to build capacity and achieve social change (Wilson, 2019). For our project, partner and community input drove every step of problem definition, designing development and deployment [Figure 2(a)]. Our early (2017–2020) activities with the partner organizations and communities included community-based mapping and monitoring of water resources and quality and sharing of locally relevant climate information from the analysis of global data sets during focus groups and workshops. Sharing and discussion of results to date took place in a July 2–3, 2019, workshop where representatives from 13 communities in the region participated. A deteriorating political situation starting in 2018 compounded by logistical challenges due to efforts to contain the COVID-19 pandemic in 2020 put in-person workshops and monitoring on hold and moved community–academic interaction online. We have continued to bridge geographic and cultural divides along with emerging technological tools. ASDENIC and the communities they serve operate exclusively in Spanish. The multidisciplinary academic team based at



**What would help you better prepare
for drought or extreme rainfall?**

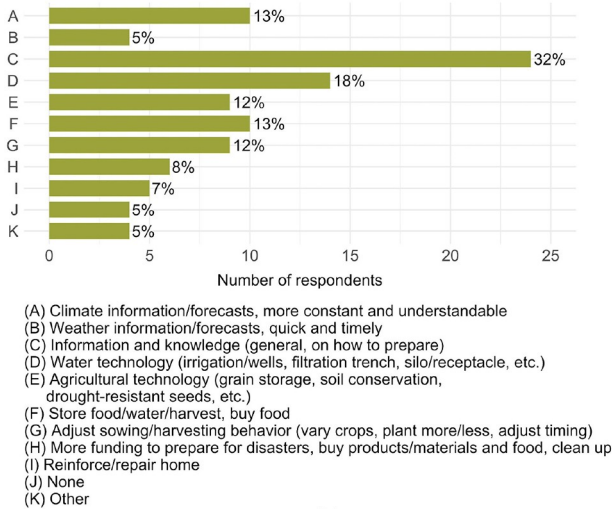


Figure 2. (a) Conceptual representation of the community involvement process for this project.
(b) Survey responses for the question on what would help better prepare for drought or extreme rainfall

Santa Clara University includes a faculty and student native speaker, two functional Spanish speakers and faculty and students from other areas of the Global South, but without any knowledge of Spanish. Conversations are routinely held in a space that bridges disciplinary divides, the academic-practitioner experience and operates in a bilingual space. All presentations and graphics have been generated in English and Spanish, often in multiple versions to improve understanding in different cultural contexts. The earliest phases of the NicaAgua app development began in 2022 and is ongoing. The baseline survey took place in mid-2022, and early focus groups in late 2022. Follow-up workshops were conducted in 2023–2024.

A principal impetus for the development of probabilistic forecasts was a workshop held on May 4, 2021, in Esteli (Nicaragua) with 2 members from the water committees (CAPS) of 13 smallholder communities, for a total of 26 community participants. In addition to facilitators from the Santa Clara University research teams and members of ASDENIC, members of the Codega municipal office were present and participated in the discussions. The workshop aimed to share research results on climatic changes in the past 40 years in the north of Nicaragua and throughout Central America, discuss strategies for managing natural resources sustainably while improving the lives of community members and a reflection about the impacts of climate change on the lives and livelihoods of participating communities, with a focus on water and protection of the ecological park where local water sources originate.

2.1.2 Survey of key challenges to water security and climate resilience. As part of the community assessment activities, we sought to understand key challenges to build local-scale water security and climate resilience under global change for smallholder farmers in northern Nicaragua. Together with ASDENIC, we co-designed a 23-question survey, centered on water access, water consumption, access to information via mobile technology, climate information and preparations for extreme events. The survey was developed during January–May 2022 in Spanish and tested through ASDENIC staff. Following this, ASDENIC trained youth promoters to administer the survey in May and June of 2022. Between July 26, 2022, and February 8, 2023, youth promoters went out to 14 communities and collected 76 valid and complete responses. All complete responses were anonymized and stored on a password-protected drive according to our approved IRB protocol. Findings from the survey were translated into English by our team, and then coded and analyzed by month/season and by access to water sources using the R open source statistical software (v. 4.4.1). We also examined the presence of any significant differences in the number of water-scarce months and the access to different water sources for various water uses.

2.2 Developing relevant, accessible, reliable and skillful forecasts and climate information for building climate resilience

Community feedback indicated the need for climate-related information, namely, short-term weather forecasts, seasonal forecasts, data from a locally maintained weather station, community communication for early warning, information on local climate change impacts and the capacity to include locally relevant knowledge. Our community–academic partnership study used the principles of frugal innovation to develop a mobile app named “NicaAgua.” Frugal innovation is the practice of developing cost-effective solutions that address the needs of resource-constrained markets, often leveraging limited resources to create high-value products or services (Ur Rehman *et al.*, 2024). Key principles include doing more with less, keeping it simple, embracing flexibility and fostering collaboration. It is about finding opportunities in adversity and designing solutions that are both effective and accessible, particularly for underserved communities. “NicaAgua” is a word play on “Nica” (local colloquial use for “Nicaraguan”), “agua” (Spanish for water) and “Nicaragua” to provide these functionalities in a manner that is accessible. To this end, all information is provided in Spanish, and language expressions and graphics were repeatedly tested with users in the community. Use of the app requires an initial registration and selection of member communities. Multiple rounds of community engagement with both ASDENIC and stakeholder communities identified short and seasonal forecasts as key features, which then were implemented using established state of the art global forecasting products. Continued engagement identified further locally relevant features that aided ASDENIC in initiating conversations on climate preparedness.

To provide short-term weather forecasts, we obtain short-term global ensemble forecasts (GEFs) of precipitation from the [Climate Hazards Center \(2025\)](#) at UC Santa Barbara, which are based on the National Centers for Environmental Prediction Global Ensemble Forecast System ([Harrison et al., 2022](#)). These are bias-corrected using Climate Hazards Center InfraRed Precipitation with Stations (CHIRPS) data, providing fine-scale quasi-global precipitation forecasts with a spatial scale of 0.05° (~ 6 km). The accuracy of these short-term forecasts was assessed by comparing the CHIRPS daily forecasts with daily precipitation totals for the times that the weather station was in operation (2022–2025).

Seasonal forecasts are based on the U.S. National Oceanographic and Atmospheric Administration (NOAA)'s North American Multi-Model Ensemble Project (NMME) and assembled by the International Research Institute for Climate and Society (IRI). The seasonal forecasts used in this study are the precipitation tercile probability forecasts produced using extended logistic regression (ELR), interpolated 1-degree (~ 100 km) latitude–longitude grid ([Kirtman et al, 2014](#); [Vigaud et al., 2017](#)). Seasonal (three-month) forecasts are issued on or about the 15th of each month with lead times of one to four months, with each grid cell and lead time having probabilities that precipitation will be below-normal, normal and above-normal.

The direct use of coarser spatial resolution forecasts such as NMME for local seasonal forecasts can involve an additional downscaling step, relating dynamically modeled precipitation to finer resolution precipitation (e.g. [Kowal et al., 2023](#)). In this study we apply the common technique of using bilinear interpolation to estimate the tercile precipitation probabilities at any point (e.g. [Cofiño et al., 2018](#); [Nyadzi et al., 2019](#)).

Assessing the skill for short-term forecasts for the Central America, we used and adapted the data provided by [Harrison et al. \(2022\)](#), where the relative mean absolute error (RMAE) was calculated by dividing the precipitation mean absolute error ($MAE = \frac{1}{n} \sum_{i=1}^n |P_f(i) - P_o(i)|$) by the mean observed precipitation ($\frac{1}{n} \sum_{i=1}^n P_o(i)$), where P is the precipitation aggregated over the forecast time window (5, 10 or 15 days), and subscripts f and o indicate forecast and observed, respectively. The MAE for 5-day and 15-day totals were forecast on the 1st, 6th, 11th and 16th of each month, dividing each by the associated mean precipitation for the same days for 2000–2019. The MAE and RMAE, by computing absolute values of deviations of forecasts from observations, have the benefit of not being overly influenced by high values. A perfect forecast would have RMAE = 0. While generally used to compare different values (such as forecasts), a smaller RMAE (< 0.4) indicates errors are small relative to the forecast values, and forecasts can be considered good (e.g. [Bodjrenou et al., 2025](#)).

2.3 A community-centered design approach to remote user experience, usability and capacity building

User experience and usability of the mobile app were evaluated through remote focus groups, while workshops with key informants and ASDENIC staff supported local capacity building. All activities were conducted remotely due to Nicaragua's political crisis following 2018, which prohibited university members from traveling to the country.

To gather user feedback efficiently, we created a remote plan for conducting focus groups. This included training ASDENIC staff on user experience (UX) data collection, holding Zoom sessions and using user interface prototypes developed with FIGMA (prototyping software). Six focus groups with 15–20 participants each were held with local community members from diverse backgrounds in terms of geography, gender, age and livelihoods as selected by community leaders.

With a more robust app, we conducted workshops aimed at enhancing local capabilities and increasing local adoption. These sessions involved community members, local leaders, international agencies and government representatives. The primary goal was to help users connect app data with climate change, supporting strategic decision-making in agriculture and local climate adaptation. A secondary objective was to strengthen the skills of local facilitators so they could share app-related knowledge with others in their communities.

All workshops and focus groups were conducted in Spanish and facilitated by ASDENIC. While designated ASDENIC observers met with participants in person, the Santa Clara University (SCU) team participated and observed remotely via Zoom. This remote collaboration ensured a community centered approach meaning both effective feedback collection and meaningful engagement with local stakeholders despite travel restrictions.

3. Results

3.1 *Leveraging community-academic partnerships for relevant forecasts*

During the pre-development focus group discussions, farmers reported recent changes in the timing and amounts of the traditional precipitation patterns and their effects on the production of both cash and subsistence crops. They repeatedly expressed the need for more reliable forecasts that are relevant for the local scale and the local decision-making process for the timing of planting, type of crop, harvesting, fertilization and pest control. ASDENIC proposed the co-development of an app through which locally relevant climate-risk information as well as data from a local weather station they are maintaining could be shared.

Survey results provided needed insights and social context into mobile phone technology penetration and digital literacy and climate information needs prior to app development. Importantly, all respondents reported having at least one smartphone (almost exclusively Android) in their household; however, internet connectivity varied significantly: 17% had constant access, 28% reported almost constant access, 50% experienced intermittent access and 7% had no access. Internet access was lowest among individuals over the age of 65 and among female respondents. This disparity may be attributed to cost-saving strategies, such as reliance on a single mobile device – often belonging to the male head of household – with cellular data rather than more expensive home Wi-Fi. To assess household-level mobile phone technological proficiency, participants were asked whether anyone in the household could download a mobile application; 91% responded affirmatively. However, among respondents over 65, 33% lacked this capability, indicating lower digital literacy. When asked about their primary sources of weather and climate forecasts, 88% cited radio and 68% mobile phones, with older individuals predominantly relying on radio and television, further underscoring age-related differences in obtaining climate information. To refine user targeting, community surveys and collaborative sessions with ASDENIC were used to identify three representative user personas: stay-at-home mothers, younger farmers and older farmers. Each group exhibited distinct information needs and engagement levels with digital tools. While stay-at-home mothers prioritized household alerts and early warnings for hazards like flash floods, older farmers focused on agricultural planning. Younger farmers shared similar agricultural interests but demonstrated higher openness to adopting and learning new technologies.

With respect to climate-related hazards, survey results also indicated that smallholder farmers actively prepare for such occurrences, particularly droughts and extreme rainfall, through a variety of household and agricultural strategies. In anticipation of extreme weather events, over half of respondents reported adjusting their planting and harvesting calendars, reinforcing homes, purchasing extra food and storing or conserving water. During drought conditions, water-related strategies such as storing water, reducing usage, and shifting crop

types were common, though a small minority (5–7%) felt they had no viable means of preparation. Access to climate and weather information was seen as a critical enabler of preparedness: 32% of respondents emphasized the importance of reliable and timely information, and many expressed interest in using forecasts to better plan agricultural activities or store essential resources. Respondents also stressed the need for improved water infrastructure – including filtration, storage tanks and rainwater collection – as vital for both immediate hazard response and longer-term climate resilience.

Notably, responses from the follow-up survey responses indicated that the smallholder farmers identified better forecasting information on climatic extremes as one of the primary needs for capacity building under climate disruption [Figure 2(b)]. More consistent and understandable climate information, weather information and information and knowledge in general together were deemed most important by 40% of the respondents. Interestingly, more information and knowledge was deemed as most important by at least twice as many respondents than agricultural technology, storing water and resources and funding for disaster preparedness. Limitations to interpreting survey results are mainly rooted in the modest survey size and the challenges of remote interaction.

3.2 *Developing relevant, accessible, reliable and skillful forecasts and climate information for building climate resilience*

3.2.1 *The functionalities and opportunities of the NicaAgua mobile app.* The resulting “NicaAgua” mobile application was developed based on the identified community needs through our collaboration between SCU’s Frugal Innovation Hub (FIH)/Water and Climate Justice Lab and ASDENIC. It is co-owned, but currently hosted on an SCU server. It provided opportunities for more than 20 graduate and undergraduate students in computer engineering, civil engineering, environmental studies and sciences and art/Web design to develop skills on a real live frugal innovation project. Based on our community engagement process, the app integrates six climate-related functionalities tailored to be accessible to rural agricultural communities through tests of user experience.

Short-term forecasts: For forward-looking planning, NicaAgua offers short-term forecasts for 5, 10 and 15 days. To provide context for the short-term forecasts, we summarize historical rainfall data from 1981 to 2020 provided by the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) program from UC Santa Barbara (Climate Hazards Group, 2014). The short-term CHIRPS-GEFS are automatically downloaded each day. The forecasts are extracted for a given cell that a community falls into and presented as a bar chart. One of our key objectives was to develop strategies on how state-of-the art climate information can be communicated in accessible and locally relevant ways. After multiple rounds of feedback, the forecasts are presented through interactive graphs accompanied by automatically generated textual interpretations. The short-term forecasts are also graphically compared to the range of precipitation of the past 40 years during the same time period (i.e. 5, 10 or 15 days) to provide a visual representation of how ordinary/extraordinary the forecast precipitation totals are. In addition, we supply summary interpretations regarding the expected precipitation totals [Figure 3(a,b)], which map numeric values to the experience of different rain intensities (i.e. light rain).

Seasonal forecasts: The application also delivers medium- and long-term seasonal outlooks, spanning one to six months (0–3 months beyond the current month and 3–6 months beyond the current month), classifying each as wetter than normal, drier than normal or normal. These are presented as a pie chart, with the percentage of the likelihood of each type of condition given as both the size of the pie slice and as a percentage [Figure 3(c)]. The app



Figure 3. (a) NicaAgua Homepage, (b) short-term (5–15 days) and (c) seasonal forecasts as presented in the NicaAgua app

flags deviations from historical climate norms through an interpretative message, enabling users to anticipate and prepare for unusual conditions.

Weather station data: A real-time display of daily local weather data collected from a community-operated meteorological station was added to the app at the request of ASDENIC. One such station, currently active in Estelí, and in operation since 2019, provides hourly updates on precipitation, temperature, wind speed and direction and dew point, along with daily forecasts. This granular data can be accessed historically, allowing users to review specific days and times for detailed weather analysis. Daily values are compiled and used to understand the differences between local experiences and the forecasts.

Broadcast alert system: A broadcast alert system enables ASDENIC administrators to disseminate timely and location-specific warnings – such as flood alerts, approaching storms or droughts, road closures or pest or disease outbreaks – to all users or targeted communities. These alerts are clearly indicated through visual cues within the app interface.

Climate change comparisons: These forecasts highlight potential anomalies in temperature or precipitation patterns by comparing projected data to 40-year historical baselines as given by the CHIRPS data (Climate Hazards Group, 2014). When these anomalies exceed expected variability, the app generates pop-up warnings to draw users’ attention to significant climate shifts. Additionally, NicaAgua includes a robust historical data feature that allows users to explore long-term climate trends. This includes four decades of precipitation and temperature records, displayed in both graphical and tabular formats, which assist farmers and decision-makers in understanding evolving climate patterns in their region.

Current moon phase: In response to feedback from user experience focus groups, we added the current moon phase as a feature in the app. Although further research is needed to address the topic of the Moon's potential influence on plant growth (Sivasankar and Thimmaiah, 2021), our users consider displaying the moon phases important for some agricultural activities, such as seeding, harvesting and pruning.

The app's most recent version, released in May 2024, introduced enhanced user interface features such as alert filtering and streamlined access to historical climate data. Technically, the app was built following principles of frugal and community-centered design, with iterative feedback collected through community workshops to ensure usability and cultural relevance. Its structure is illustrated in Figure 4. Administrators manage station data and alerts through a dedicated Web dashboard, facilitating regular updates and community engagement. Overall, NicaAgua serves as a comprehensive decision-support tool that integrates real-time data, climate forecasts and long-term trend analysis to help rural communities adapt and strategize actions to cope with climate variability and build resilience in the face of environmental change.

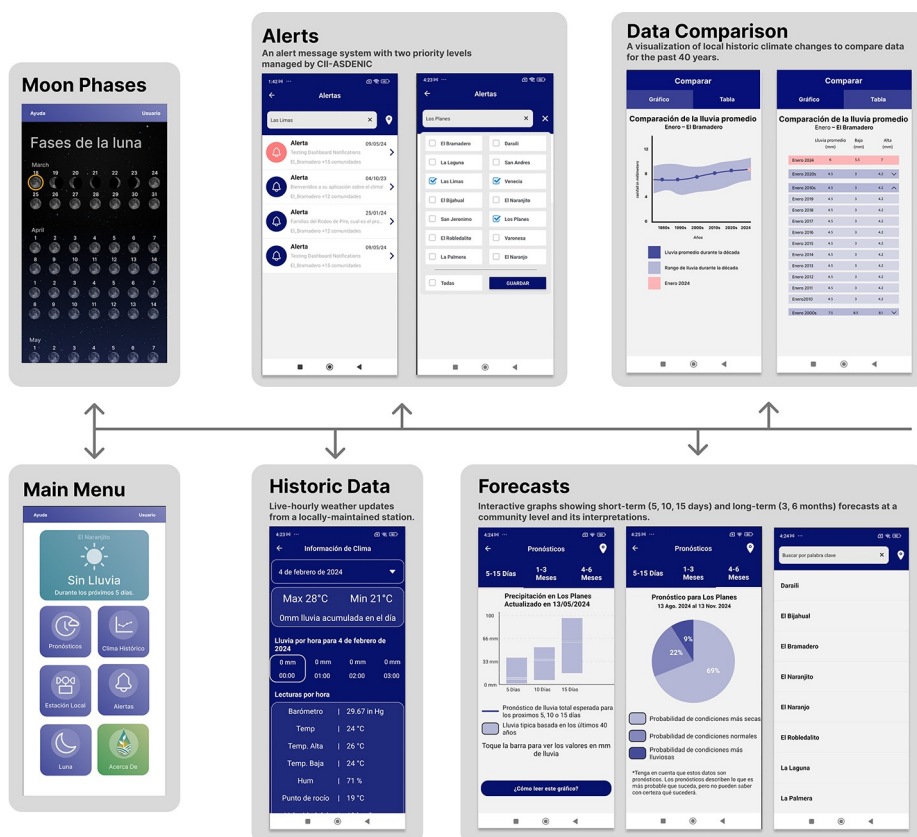


Figure 4. The structure and functionalities of the *NicaAgua* mobile application

A number of participatory climate-related mobile apps have recently been developed for the Global South. In Central and South America, SmartCampo (EnsoAg LLC, 2023), GuiaClima (Empresa Brasileira de Pesquisa Agropecuária, 2024), Booster Agro (Booster Ag Tech, Inc., 2022), AgrosystemCloud (Agrosystem Tecnologia, 2020) and Climatica (Ingemann Data A/S, 2024) provide climate forecasts. Except for Climatica, none of the other apps provides forecasts for Nicaragua. NicaAgua differs from Climatica and the other mobile app products in several key ways, namely, it is connected with partner organizations on the ground that are capable of sending alerts and uploading information of their local weather stations to the app; does not limit users by location or request a user or password, making it easier to access the app; is transparent about the underlying sources of climate data and their accuracy; provides comparisons between current to historic climatic patterns; NicaAgua provides information about the moon phases, which is used for certain traditional agricultural activities; and is used as a tool to study climate resilience by the developers and partner organizations.

3.2.2 How skillful and reliable are the forecasts from the NicaAgua app? For short-term forecasts, the skill in Central America is evident (Harrison *et al.*, 2022). The higher skill for five-day rainfall forecasts are from June–August, with the best skill (RMAE of 20–40%) in central Nicaragua and toward the Caribbean coast. The early rainy season (May in particular) shows less skillful forecasts (RMAE > 60%). The 15-day short-term forecasts show reasonable skill throughout Nicaragua (RMAE < 40%) for most of the rainy season, from June onward (Figure 5). Comparison of short-term forecasts with the actual precipitation totals from the local weather station indicated that the strongest agreements exists in the No Rain category, indicating high reliability of satellite detection in identifying dry periods that are confirmed by the on-the-ground weather stations and (b) less agreement for moderate heavy rainfall events.

For seasonal forecasts, a common measure of the skill of tercile probabilities is the ranked probability skill score (RPSS), the details of which are described in many references (Murphy, 1973; Wilks, 1995). In general, the RPSS can be applied to forecasts that are expressed as probability distributions, and it describes their skill in matching observed outcomes, with a maximum value of 1.0. Positive values represent positive skill over a forecast of random chance. The approximate relationship between RPSS and correlation is that an RPSS value of 0.1 corresponds to a correlation of about 0.44 (Tippett *et al.* 2010). Seasonal skill scores based on the historical performance of the calibrated NMME models have been calculated by the IRI, from whom seasonal forecasts are obtained for this project. The skill scores are based on hindcast verification experiments conducted by IRI using the same NMME ensemble as current IRI seasonal forecasts (based on models CanSIPS-IC3, CFSv2, COLA-RSMAS-CCSM4, GFDL-SPEAR and NASA-GEOS2S) and using CAMS_OPI precipitation (Janowiak and Xie, 1999) observations from 1991 to 2020. These skill scores are shown in Figure 6.

Figure 6 shows that, for forecasting the May–October rainy season, positive skill exists for seasonal forecasts, especially for the later wet season (July–October). For example, the April forecast shows reasonable skill throughout central and western Nicaragua at leads of three (forecasting JAS) and four (forecasting ASO) months. While this large-scale skill cannot forecast short-term extremes or anomalies at local scales, they can provide meaningful skill for the later rainy season.

3.3 A community-centered design approach to remote user experience, usability and capacity building

Development of the mobile app and community input has been a cyclical process that has led to several phases of revision and redevelopment. In our earlier user experience focus groups,

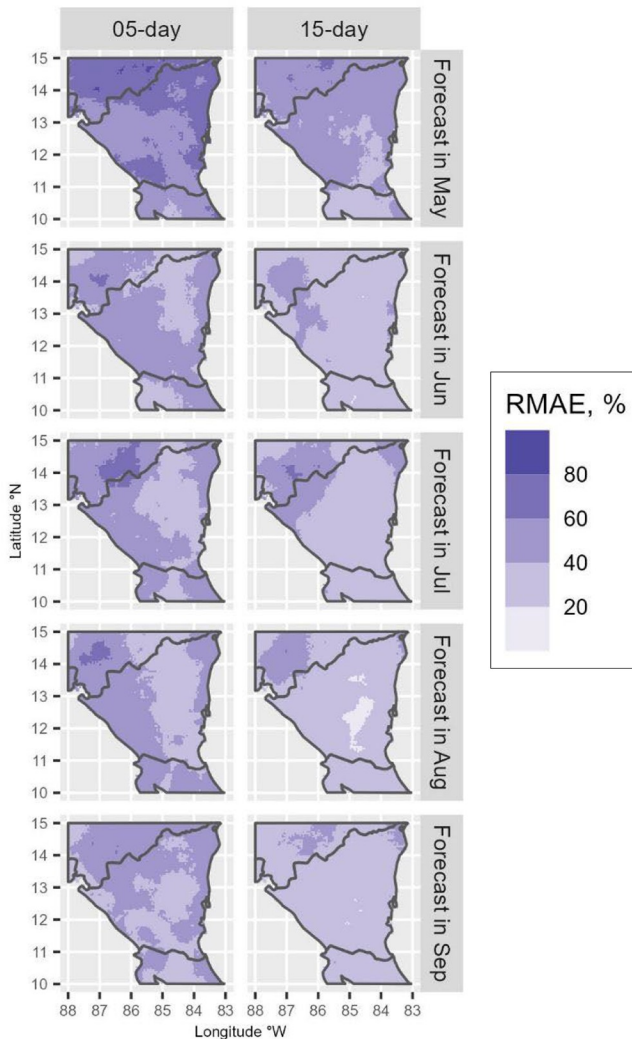


Figure 5. RMAE values for Nicaragua for 5-day and 15-day forecasts during the rainy season made on the 1st, 6th, 11th and 16th of each month

we found older and younger participants engage with climate information, climate forecasts and technology in different ways. While older participants were able to relate information to years of day-to-day experiences of navigating weather and farming activities, they struggled with navigating the different technical aspects with the app, such as installing and opening the app, identifying how to navigate and interpret the different functionalities and identifying data relevant to a question. Once a facilitator stepped through the processes with them, they appreciated the utility of the data. By contrast, younger participants were less able to link the information on weather and climate to farming activities, but had little or no trouble to install

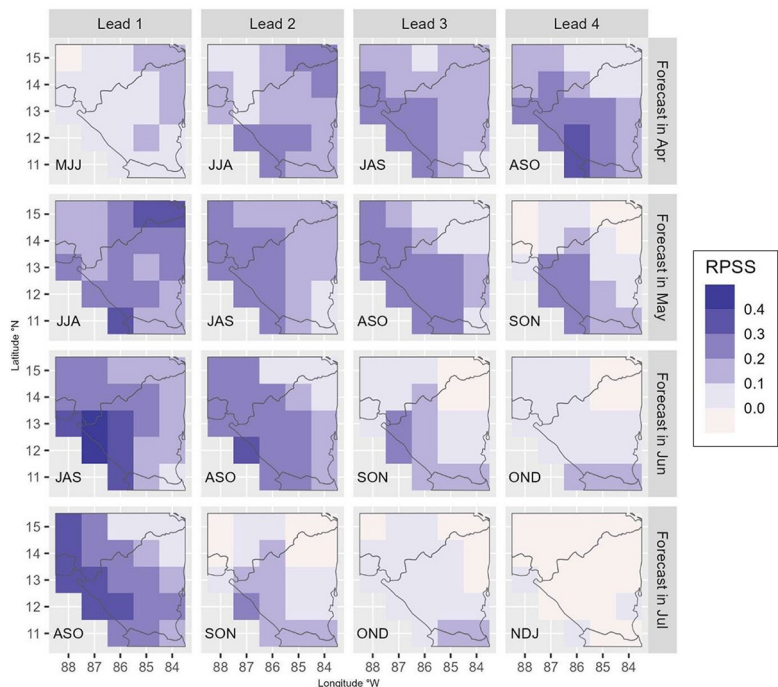


Figure 6. RPSS values for forecasts issued April through July, labeled on the right axis, for varying lead times over Nicaragua. The month the forecast is issued is Month 1 (mid-month). Lead 1 = Months 2–4, Lead 2 = Months 3–5, Lead 3 = Months 4–6, Lead 4 = Months 5–7 after the forecast is issued. The forecast seasons are labeled in each panel (e.g. MJJ = “May–July”)

the app, register for the service and navigate the different functionalities. Connectivity for installation was a concern during the focus groups and workshops and needs to be taken into consideration for app development.

For the short-term forecasts, two key aspects noted by focus groups participants were how to connect “mm of depth of precipitation” to an understanding that enables smallholders to make decisions for agricultural activities (i.e. about planting, irrigating or watering) or disaster preparedness (i.e. extreme precipitation events or droughts that would necessitate the storage of water and food, securing family and property and other mitigation strategies). Focus groups participants were able to connect with the concept of actual precipitation forecasts, but some of them struggled with the idea of interpreting how “normal” or extraordinary’ these amounts were. We also learned from workshop and focus group feedback that interpreting the combined likelihoods of wetter, drier and normal conditions presented as pie charts [i.e. Figure 3(c)] in medium-range forecasts presented significant interpretive challenges. Through reiterative adaptation on how data are presented based on feedback from workshops, focus groups and community partners, we have worked to gradually address these challenges.

To address the aspect of how farmers could connect a depth of rainfall predicted to an interpretation or actual experience of rainfall that enables decision making support (i.e. too wet/dry for planting or harvesting). For each community served by the app, we used 40 years

of CHIRPS data to analyze the depth of rainfall that would correspond to the >0, 10th, 25th, 50th, 75th or 90th or >99.9th percentile which have been labeled as “no rain,” “very light rain,” “light rain,” “moderate rain,” “heavy rain,” “very heavy rain,” and “extreme rain” by weather forecasting services. These designations can then be included in a message below short-term forecasts. Extreme rains in this context are those of more than 200 mm over 10 days.

To respond to difficulties encountered with the likelihoods of forecast medium-term conditions, we have provided to users an automatic interpretive messages below the graphic that expresses the date range for which the forecast is made, as well as which condition(s) are going to be likely, and a measure of the confidence level associated with those forecasts (see [Figure 3](#)). The confidence level is dependent on the relative magnitude of each condition, and it is translated into messages that indicate a given condition as “somewhat likely” or likely.

Other key feedback received from the focus groups that helped improve the app’s usability included enlarging icon sizes to accommodate users who work in the field and may have thicker fingers. Additionally, during multiple sessions, users experienced issues with the app like crashing or not opening at all. Initially, we believed these issues were directly related to the app itself. However, after further testing, we discovered that the problems were caused by poor or unstable connectivity. To enhance the user experience, we implemented an alert system that notifies users when they are experiencing connectivity issues.

Outcomes from focus groups and workshops have indicated that how information is presented plays a large role in making information understandable and therefore accessible. While other weather and forecasting apps exist, this project is unique, in that it is combining these forecasts with information on climatic shifts, and metrics relevant to local agricultural decision making. In addition, we explore the possibilities and challenges of doing community-based work remotely through a local partner. Resourcing is an important consideration for knowledge transfer. For the near term, app hosting, maintenance and updating will remain with SCU’s Frugal Innovation Hub, whose innovation-based design and tech stack seeks to keep monthly maintenance costs low. For the mid- to long-term strategy, we are exploring collaborations with a local university in northern Nicaragua and expanding the NicaAgua app to other areas in Central America through a grant.

4. Discussion

This work is motivated by the need to understand how global-scale climate forecasts can be adapted for use at the community level in regions most vulnerable to climate change. Central to this challenge is not only the technical task of downscaling climate information but also the need to ensure accessibility and relevance for local stakeholders, particularly smallholder farming communities. Our interdisciplinary approach addresses this gap by bridging global short- and medium-term forecasts with locally contextualized information, evaluating forecast skill and making these data accessible through the NicaAgua mobile application. This tool integrates visualizations and interpretive content to support agricultural decision-making, aiming to enhance both adaptive capacity and climate resilience.

In Central America, where climate vulnerability intersects with limited data infrastructure, the NicaAgua project advances localized adaptation strategies. A distinctive feature of this initiative is its use of the CBPAR framework, embedding forecasts within the knowledge systems, priorities and lived experiences of local stakeholders. The app was initiated by and is further supported through climate change mitigation workshops and locally generated weather station data managed by our NGO partner, reinforcing the co-production of knowledge and the sustainability of the intervention. However, significant challenges remain:: translating global climate models to the community scale in areas where

weather station coverage is sparse reduces the skill and accuracy of the forecasts, a deteriorating political situation reduces interactions of the partnership to, the NGOs capacity to engage in climate adaptation discussions on the ground is limited, technical capacity is limited and the impacts of climate change are acutely felt.

Effective bottom-up capacity building depends on decision-support tools that are both stakeholder-centric and grounded in rigorous climate science. Implementation must be carefully tailored to local contexts – considering climate variability, agricultural practices, socio-economic conditions and institutional roles. Moreover, building climate resilience cannot occur in isolation; it must also align with broader sustainable development objectives such as food and water security, poverty alleviation and economic development. In this regard, tools like NicaAgua offer an important framework for integrated adaptation planning. ASDENIC highlighted the opportunity that NicaAgua provides to face the challenges of the present and future, taking into account that by putting decision-making tools through technology in the hands of young people. For such tools to be effective, however, they must remain dynamic – evolving continuously in response to stakeholder feedback, changing environmental conditions and emerging scientific insights. Long-term commitment, institutional partnerships and community ownership are critical to sustaining these efforts in resource-constrained settings such as northern Nicaragua.

While the present study employs two widely used forecast products, we acknowledge that other forecasting systems offer promising alternatives for future integration. For instance, NASA's SERVIR project uses the North American Multi-Model Ensemble (NMME) seasonal forecasts for precipitation and temperature, which are bias-corrected and downscaled to a 0.5° (~50 km) resolution to support applications such as crop production modeling (Flores Cordova *et al.*, 2012). Similarly, the SEAS5 system developed by the European Centre for Medium-Range Weather Forecasts produces high-resolution (~36 km) seasonal precipitation forecasts, which have demonstrated useful skill in Central America at lead times of up to six months (Kowal *et al.*, 2021). These and other products illustrate the ongoing evolution of climate forecasting systems and the opportunity to refine local applications through enhanced resolution and accuracy.

By using interpolated forecast data directly, we have not added any additional products to what is distributed to farmers. Many climate services provide refined forecasts or additional products of interest to stakeholders (e.g. Hazra *et al.*, 2023; Sotelo *et al.*, 2020; Walker, 2021).

Combining short-term weather forecasting with long-term climate change analysis presents significant opportunities for smallholder farmers, particularly in regions vulnerable to climate variability. While daily and seasonal forecasts support immediate agricultural decisions – such as planting schedules, irrigation management and pest control – long-term climate data equip farmers with the insight needed to adapt their practices to shifting environmental baselines. This dual approach enables more resilient planning, such as transitioning to drought-tolerant crops or adjusting sowing dates in anticipation of changing rainfall patterns. By integrating both temporal scales of information, farmers are better positioned to reduce risk, enhance productivity and build adaptive capacity in response to both immediate weather events and gradual climatic shifts. Continued feedback from stakeholders will guide future work.

Technical and thematic tools, such as the NicaAgua app, can serve as effective frameworks for building capacity. To ensure long-term impact, these tools must prioritize sustainability – through local hosting, ongoing maintenance and open-source development – and be regularly adapted to meet stakeholder needs. In regions like Northern Nicaragua, long-term commitment, partnerships and trust-building are essential for successful adoption. Continued research is critical, as many global regions must strengthen their adaptive capacity to respond to climate change-driven extreme events.

5. Conclusions

This study highlights the critical challenge of translating global-scale climate forecasts into actionable, community-scale tools for data-scarce, climate-vulnerable regions. Through the development of the NicaAgua mobile application and an interdisciplinary approach grounded in CBPAR, we demonstrate how scientific innovations can be localized to support agricultural decision-making and capacity building among smallholder farmers in northern Nicaragua. A central opportunity lies in combining short-term forecasts with long-term climate trend analysis, enhancing both immediate responsiveness and strategic adaptation. Challenges include the limited availability of localized meteorological data and the difficulty of downscaling and validating forecasts in areas with sparse observational infrastructure. Addressing these gaps requires sustained partnerships, iterative stakeholder engagement and adaptation of technical tools to reflect local agricultural systems, socio-economic contexts, and evolving climate risks.

Our work underscores the need for stakeholder-centric decision-support systems that bridge scientific capacity and community needs while advancing sustainable development goals such as food and water security. Although we employ widely used forecast products, future iterations of the NicaAgua app could integrate higher-resolution and locally bias-corrected forecasts, to improve spatial precision and usability. Ultimately, advancing climate resilience in vulnerable farming communities requires not only technical innovation but also long-term commitment to participatory, localized implementation. As extreme weather events intensify globally, such integrative and adaptive models of climate services will be essential for building robust, locally embedded systems of support.

Acknowledgements

The authors thank Helen Hernández Blandón (ASDENIC) and a multidisciplinary team of SCU students, namely, Abhilash Harish Srivathsa, Alexa Grau, Alexander Avila, Alexander William, Chandan Dhamande, Gautam Chitnis, Giuliano da Silva, Greta Seitz, Justin Ling, Melody Trinh, Nicolas Gibson, Rachael Freitag, Sara Wheeler, Sarah Ortiz, Sudarshan Mehta, Tanmay Singla, Turner Uyeda and Victoria Luo, for their contributions. The authors gratefully acknowledge funding by the Whitham Foundation and the Miller Center for Global Impact at Santa Clara University.

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