



Research Article

From Climate Information to Agricultural Decisions: Understanding the Needs of Smallholder Farmers in Bangladesh

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Abstract

Climate information can support smallholder farmers in managing increasing weather- and climate-related risks, but access to information alone does not ensure that it can be effectively used in agricultural decision-making. This exploratory qualitative study examines the climate information needs and digital information experiences of 12 smallholder farmers in Sherpur District, rural Bangladesh. Drawing on semi-structured interviews, the study investigates how farmers receive and use climate information, the barriers they encounter with digital delivery mechanisms, and how information needs vary across crops, farming activities, and livelihood strategies. The findings indicate that the usefulness of climate information depends not only on timely delivery but also on its relevance to specific crops, production stages, and agricultural activities. Farmers engaged in diversified livelihoods, including both crop cultivation and fish farming, face additional information needs that may not be adequately addressed by crop-focused services. Digital channels such as SMS and smartphone applications offer opportunities for rapid information delivery but also present challenges related to information retrieval, digital literacy, and accessibility. The study argues for a shift from information delivery toward contextualized decision support and proposes a hybrid approach combining concise digital alerts with periodic offline communication and locally relevant guidance. To address these challenges, the study proposes the Bidirectional Participatory Climate-Agro Advisory Framework (BP-CAAF), a conceptual framework that combines climate forecasts, extension support, and farmer feedback. BP-CAAF introduces a two-way information process in which farmers not only receive advisories but also contribute local observations and assessments of advisory usefulness. By connecting forecasting institutions, extension systems, and farming communities, the framework aims to improve the relevance, trustworthiness, and actionability of climate information services.

Keywords

Climate Information Services, Smallholder Farmers, Agricultural Decision-Making, Digital Agriculture, Climate Adaptation, Bangladesh.

1. Introduction

Climate change poses significant challenges to agricultural livelihoods in rural Bangladesh (World Bank, 2022). Smallholder farmers are increasingly exposed to floods, cyclones, drought, excessive rainfall, heat, and other climate-related risks that can affect crop production, aquaculture, household income, and decisions about land use (Kumar et al., 2021; World Bank, 2022). For farmers whose livelihoods depend heavily on agriculture, timely and reliable climate information can help them make decisions about planting, harvesting, irrigation, crop selection, fish management and

preparation for extreme weather events (Born et al., 2021; Kumar et al., 2021).

However, farmers do not constitute a homogeneous group. They may cultivate different crops and varieties, including different types of paddy, vegetables such as cucumber, and other seasonal crops. The relevance of climate information can therefore vary considerably across crops. A rainfall forecast that is useful for one crop or stage of cultivation may be less relevant to another. Similarly, information about temperature, flooding, water availability, or the timing and duration of rainfall may have different implications depending on the crop, variety, soil conditions, and stage of production. Climate information services therefore need to consider not only whether information reaches farmers, but also whether it is sufficiently specific to the crops and farming activities that farmers actually manage.

Farmers may also combine crop production with other livelihood activities. Some households, for example, engage in fish farming in addition to crop cultivation. Climate conditions can affect these activities differently and may create interconnected risks and decisions. Heavy rainfall or flooding may have implications for both crops and fishponds, while changes in temperature and water conditions may affect aquaculture. Consequently, farmers may need climate information that supports decisions across multiple agricultural activities rather than information focused on a single crop.

Land-use decisions also form part of the livelihood strategies of some rural households. In some cases, farmers may lease agricultural land to brick producers because doing so provides an alternative source of income. Although such arrangements may generate short-term financial benefits, brick production can also have implications for soil fertility, land productivity, and the long-term agricultural potential of the land. These decisions illustrate that farmers' responses to economic and environmental pressures cannot always be understood as conventional agricultural adaptation. Climate and agricultural information services may need to be situated within a broader understanding of household livelihood decisions and their environmental consequences.

Digital technologies offer an important opportunity to expand access to climate information. Farmers can receive weather and climate information through short message service (SMS), mobile applications, social media, voice messages, and other digital platforms. Compared with traditional face-to-face communication, digital systems can potentially distribute information to large numbers of farmers quickly and at relatively low cost.

However, access to information does not necessarily mean that farmers can effectively use it. Interviews conducted for this exploratory study suggest several challenges with current digital delivery systems. Some farmers reported difficulty tracking and retrieving information received through SMS. Smartphone-based applications may also exclude farmers who do not own smartphones or who have limited digital literacy. More fundamentally, even when information is successfully delivered and understood, it may not be sufficiently tailored to the crop, farming activity, or livelihood decision facing a particular farmer, a challenge widely noted in studies of climate service usability (e.g., Warner et al., 2022; Madhuri, 2023).

This study therefore examines climate information not only as a communication service but as a resource for agricultural and livelihood decision-making. It asks: (1) What challenges do farmers experience when receiving climate information digitally? (2) What makes climate information useful and actionable for different crops and farming activities? (3) How do farmers with mixed livelihoods, including crop and fish farming, use or need climate information? and (4) How could digital and offline communication channels be combined to improve access, interpretation, and actionability?

Based on the findings, the paper introduces the Bidirectional Participatory Climate-Agro Advisory Framework (BP-CAAF). While existing research has demonstrated the value of participatory and co-produced climate information services, including in Bangladesh (Kumar et al., 2021), BP-CAAF proposes a more explicitly structured bidirectional advisory architecture. The framework integrates two complementary feedback mechanisms: farmer-reported observations of local environmental conditions and farmer evaluations of advisory usefulness. It further proposes a spatial consensus mechanism for assessing crowdsourced observations and incorporates crop-specific and mixed crop-aquaculture information needs into localized advisory generation. These elements represent a conceptual extension of existing participatory approaches rather than an empirically validated alternative.

2. Literature Review

2.1. Climate Vulnerability and Agricultural Decision-Making

Agricultural production is highly dependent on weather and environmental conditions. For smallholder farmers, unexpected rainfall, flooding, drought, or extreme temperatures can cause significant losses. Climate information can reduce some of this uncertainty by allowing farmers to anticipate weather conditions and adjust their agricultural practices accordingly (Born et al., 2021; Madhuri, 2023).

The usefulness of climate information, however, depends partly on the agricultural activity to which it is applied. Different crops and varieties have different water, temperature, and growing-season requirements. Even within rice production, different paddy varieties may have different sensitivities to flooding, drought, temperature, and the timing of rainfall. Vegetable crops such as cucumber may respond differently to excessive rainfall, heat, or waterlogging. Consequently, climate information should not necessarily be treated as universally applicable across all farming activities.

Climate information can be useful at different time scales. Short-term forecasts may help farmers decide whether to plant, irrigate, apply inputs, harvest, or protect crops from heavy rainfall. Longer-term seasonal information can support decisions about crop varieties, planting periods, water management, and broader production strategies. For farmers involved in aquaculture, information about rainfall, temperature, flooding, and water conditions may also influence fish-management decisions.

This suggests that the value of climate information depends on the relationship between forecast information, agricultural context, and decision timing. Information is most useful when farmers can connect it to a specific decision affecting a particular crop, variety, farming activity, or stage of production.

2.2. Mixed Farming and Livelihood Decisions

Smallholder livelihoods are often diversified rather than based on a single agricultural activity (Nyoni et al., 2024). A household may combine crop cultivation with fish farming, livestock, wage labor, or other sources of income. Such diversification can influence the type of climate information farmers need.

For example, a farmer managing both crops and fishponds may face different risks from the same weather event. Heavy rainfall could create risks for standing crops while simultaneously affecting pond water levels and fish management. A climate information service designed exclusively around crop production may therefore fail to address the full range of decisions faced by households with diversified agricultural activities.

Understanding climate information needs therefore requires attention to the livelihood portfolio of the farmer or household, rather than assuming that all users have the same agricultural information requirements.

2.3. Land Use, Brickmaking, and Environmental Trade-offs

Farmers' responses to economic pressures can also involve changes in land use. Leasing agricultural land for brick production can provide income to landowners or farmers, particularly when agricultural returns are uncertain. Research in Bangladesh has shown that selling agricultural soil for brickmaking can provide short-term financial benefits while adversely affecting agricultural productivity (Biswas et al., 2018). Brickmaking may also involve removal or disturbance of topsoil, with consequences for soil fertility and future agricultural productivity.

This issue introduces an important dimension to the study: farmers' decisions are not necessarily limited to choosing how to manage a crop in response to climate conditions. They may also involve decisions about whether to continue agricultural production, diversify livelihoods, or temporarily or permanently use land for other purposes.

Climate information services alone cannot resolve these broader economic and environmental trade-offs. Nevertheless, understanding such decisions is important for designing agricultural information systems that recognize the realities of rural livelihoods. Information services may need to connect climate information with broader agricultural extension, land-management, and environmental guidance.

2.4. Digital Delivery of Climate Information

Mobile phones and digital platforms have expanded the potential for agricultural extension and climate information services (Aker, 2011; Fabregas et al., 2019). SMS can reach farmers without requiring an internet connection, while smartphone applications can provide more detailed information and interactive services. Digital communication can also allow information to be distributed more frequently than traditional face-to-face extension services.

Despite these advantages, digital delivery has limitations. SMS messages can become difficult to retrieve when farmers receive many other messages. Smartphone applications may require devices, internet access, and digital skills that are not equally available among rural households. Consequently, digitalization may improve access for some farmers while creating barriers for others (Warner et al., 2022).

An additional challenge is contextualization. Even when farmers receive and understand a forecast, they may still need assistance interpreting what that information means for a particular crop, variety, fish pond, or land-use decision. This reinforces the potential importance of agricultural extension workers and other local intermediaries.

2.5. State of the Art and Research Gap

Recent climate-information-services research increasingly treats climate information as an input to decisions rather than as a product whose success can be measured only by delivery. [Born et al. \(2021\)](#), in a global meta-analysis, organize the literature around climate-influenced farm decisions and show the importance of matching climate variables and forecast timescales to particular management choices. This decision-centered perspective is directly relevant to smallholder agriculture because the value of a forecast depends on when it arrives and the action available to the farmer.

Research also shows that access does not automatically result in use. [Warner et al. \(2022\)](#) identify sociocultural and demographic conditions, program design, institutional support, trust, timeliness, and communication processes as recurring influences on the uptake of agricultural climate information. [Madhuri \(2023\)](#) similarly finds that interpretation difficulties, accessibility constraints, and weak connections between forecasts and stages of the farming cycle can limit adaptation. These reviews indicate that usability and actionability depend on more than forecast accuracy or technical availability.

Farmer heterogeneity further shapes the adoption and value of climate information. [Nyoni et al. \(2024\)](#) use a sustainable-livelihoods perspective to show that human, social, physical, financial, and natural resources influence smallholders' access to and use of climate information services. Education, information and communication technology skills, advisory support, and farm resources can therefore determine whether the same service is useful to different farmers. However, much of this evidence is drawn from African studies outside Bangladesh and emphasizes adoption at a broad level rather than the relationship among specific crops, production stages, and immediate decisions.

A Bangladesh-specific study provides the closest foundation for the present study. [Kumar et al. \(2021\)](#) demonstrate in the Lower Bengal Delta that co-produced forecast visualizations, farmer field schools, printed material, face-to-face interaction, and smartphone applications can improve understanding, trust, and uptake. Their findings strongly support combining digital communication with human interpretation and capacity building. Nevertheless, the study does not make within-household variation across crop types, production stages, mixed crop-aquaculture activities, and message retrievability its central analytical focus.

Taken together, the literature shows a progression from information provision toward user-centered, co-produced, and decision-relevant climate services. Yet less is known about how climate-information needs vary within heterogeneous smallholder livelihood portfolios in rural Bangladesh: across crops and varieties, stages of production, combinations of crop farming and aquaculture, and farmers with different digital capabilities. The present study addresses this gap by examining not only whether information reaches farmers, but whether it remains retrievable, interpretable, context-specific, and actionable for the particular agricultural and livelihood decisions they face.

Table 1: State of the Art in Climate Information Services for Smallholder Agricultural Decision-Making

Study	Context / Scope	Contribution Relevant to This Study	Remaining Gap
Born et al. (2021)	Global meta-analysis of climate services and farm decisions	Maps forecast variables and time-scales to agricultural decisions	Underlying studies often lack detailed crop and local-context information
Kumar et al. (2021)	Smallholders in the Lower Bengal Delta, Bangladesh	Shows value of co-production, visual forecasts, smartphones, print, and face-to-face support	Does not centrally compare crop-stage, mixed-livelihood, and retrieval needs
Warner et al. (2022)	Systematic review of agricultural CIS use	Identifies trust, timeliness, participation, communication, institutions, and resources as conditions of use	Explains enabling conditions more than activity-specific decision requirements
Madhuri (2023)	Systematic review of CIS and adaptation strategies	Highlights interpretation, accessibility, forecast format, and links to farming cycles	Limited evidence on within-household combinations of crops and other activities
Nyoni et al. (2024)	Systematic review of African smallholders	Shows how livelihood assets, ICT skills, and advisory services shape adoption	Africa-focused and primarily concerned with broad adoption and targeting

Source: Author's compilation from the cited literature.

2.6. Theoretical Framework: Co-Production and Participatory Sensing

Addressing the climate information usability gap ([Lemos et al., 2012](#)) requires theoretically grounding digital advisory systems in established models of co-production and participatory design that recognize farmers as active contributors

to the development and improvement of climate information services (Bremer et al., 2019; Vincent et al., 2018). While traditional agricultural extension in Bangladesh and many parts of South Asia has largely relied on top-down models of information dissemination (Sarker & Itohara, 2009), the emergence of mobile-enabled digital agriculture (often framed as information and communication technologies for development, ICT4D) demonstrates significant potential to empower smallholders and enhance decision-making when designed around local socio-technical realities (Aker, 2011; Fabregas et al., 2019; Madhuri, 2023). Beyond disseminating information, digital platforms can also enable farmers to contribute observations and experiential knowledge back into advisory systems. The literature on participatory sensing and farmer citizen science demonstrates how smallholder farmers can contribute observations and experiential knowledge to agricultural research rather than remaining passive recipients of information (Ryan et al., 2018; van Etten et al., 2019). Although these studies primarily examine citizen science and participatory crop-variety evaluation rather than climate advisory feedback, they provide a conceptual foundation for exploring how farmer-generated observations could contribute to the development of more locally relevant climate information services. Integrating such participatory mechanisms into advisory systems can strengthen their credibility, legitimacy, and perceived usefulness among users, which are essential conditions for the uptake of climate information and adaptation recommendations (Carr et al., 2020; Cash et al., 2003; Vaughan & Dessai, 2014). In Bangladesh, where agricultural extension initiatives are increasingly embracing digital and climate-smart approaches (Uddin & Siddique, 2024), incorporating bidirectional crowdsourced feedback offers a promising pathway for transforming one-way information delivery into responsive, locally grounded, and co-produced agro-climate advisory services.

These theoretical perspectives inform the proposed Bidirectional Participatory Climate-Agro Advisory Framework (BP-CAAF). The study findings highlight farmers' needs for localized, crop-specific, and actionable climate information, alongside challenges associated with digital accessibility and information retrieval. Building on these findings and the principles of co-production and participatory sensing, BP-CAAF proposes integrating institutional climate forecasts with farmer-reported observations and evaluations of advisory usefulness. These feedback mechanisms represent conceptual design proposals whose feasibility and effectiveness require further empirical validation.

3. Methodology

This study uses an exploratory qualitative research design based on semi-structured interviews with smallholder farmers in rural Bangladesh. The objective is to provide exploratory insights into farmers' experiences with digital climate information and to identify potential areas for improving service design.

3.1. Study Area and Socio-Ecological Context

Empirical fieldwork was conducted in two distinct agricultural communities located within Sherpur District, an agrarian region situated in north-central Bangladesh. This district was chosen for its exposure to climatic volatility and its mix of farming systems. The area lies within the Old Brahmaputra floodplain and experiences significant monsoon rainfall, seasonal dry spells, and high susceptibility to riverine floods and pre-monsoon thunderstorms (locally known as Kalbaishakhi).

The agro-ecological landscape in Sherpur is defined by low-lying alluvial plains crisscrossed by rivers and canals. Landholdings are highly fragmented, with individual farming households often managing non-contiguous plots scattered across different land elevations. The primary cropping patterns include high-yielding variety (HYV) monsoon rice (Aman), irrigated winter rice (Boro), and high-value winter vegetables. In recent years, unpredictable rainfall and water management challenges have driven some households to convert low-lying paddy plots into commercial freshwater fishponds, creating an integrated crop-aquaculture production system that informs a key part of this study's analysis.

3.2. Participant Sampling and Field Protocol

A purposive sampling strategy was used to capture a wide spectrum of technological exposure, farm scales, and production practices. A total of twelve smallholder farmers (N = 12) were selected across the two villages. Criteria for inclusion required that participants: (1) actively manage a farm holding of less than 2.0 hectares; (2) derive their primary household income from agricultural production; and (3) have had regular exposure to digital climate or agricultural information for at least one complete crop calendar year. This approach was chosen to ensure participants could speak directly to the challenges and opportunities of existing digital advisory services. The two study villages were predominantly rural and agricultural. Participants were identified through local contacts who facilitated introductions to prospective interviewees. All 12 participants were men.

3.3. Data Collection and Analysis

Fieldwork was conducted between October 2025 and February 2026. In-depth, semi-structured interviews were carried out in Bengali, lasting between 30 and 45 minutes each. The interviews were documented through handwritten field notes rather than audio recordings. Verbal informed consent was obtained from each participant before the interview, and the consent was documented in the researcher’s handwritten field records.

A structured interview guide was used to explore four primary domains:

- 1. Channels of weather and agricultural knowledge acquisition.
- 2. The usability and practical application of digital advisories.
- 3. Technical and functional friction experienced when accessing digital information.
- 4. The alignment between advisories and the realities of managing mixed-crop plots and aquaculture.

The interviews also explored livelihood diversification, including questions about combined crop–fish cultivation and decisions to lease land for non-agricultural purposes. Because the study uses a small, purposive sample, its findings should not be interpreted as representative of all farmers in Bangladesh. Instead, the analysis provides exploratory insights that form the operational basis for the proposed framework. The demographic and agricultural profiles of these 12 participants are detailed in Table 2 to provide clear contextual framing for the qualitative findings.

Table 2: Summary of Participant Demographic and Agricultural Characteristics (N = 12)

ID	Age Range	Gender	Education	Farm Size (ha, approx.)	Primary Farming Activities	Fish Farming (Y/N)	Digital Tool Experience
P01	35–45	Male	Secondary	1.6	Rice, Vegetables, Mustard	Y	Experienced
P02	56–65	Male	None	1.2	Rice, Vegetables	N	Novice
P03	46–55	Male	Primary	1.5	Jute, Rice	Y	Novice
P04	35–45	Male	Primary	1.2	Rice, Vegetables	N	Novice
P05	25–34	Male	Higher Ed.	0.8	Rice, Mustard	Y	Experienced
P06	46–55	Male	Secondary	1.0	Potato, Rice, Vegetables	Y	Intermediate
P07	56–65	Male	Primary	0.8	Rice, Mustard	N	Novice
P08	35–45	Male	Primary	1.3	Rice, Poultry	N	Intermediate
P09	35–45	Male	Secondary	0.9	Rice, Vegetables	Y	Intermediate
P10	25–34	Male	Higher Ed.	0.7	Potato, Rice, Vegetables	Y	Experienced
P11	56–65	Male	None	1.0	Rice, Vegetables, Wheat	N	Novice
P12	46–55	Male	Primary	1.2	Rice, Jute	Y	Novice

Note: Digital Tool Experience refers to participants’ general familiarity with and ability to use mobile phones and mobile applications, rather than their experience with agricultural or climate advisory services. Novice indicates limited proficiency; Intermediate indicates the ability to use common phone functions and some applications with limited proficiency; and Experienced indicates greater confidence in independently using mobile phone functions and applications. These categories reflect descriptive assessments rather than scores from a standardized digital-literacy test. All 12 participants were men. Smartphone ownership is reported in aggregate in Section 4.5, while land-leasing experiences are described qualitatively in Section 4.3, because participant-level information for these characteristics was not available for inclusion in the table. A retrospective summary of the main interview topics is provided in Appendix A; this summary does not reproduce the original interview questions verbatim.

3.4. Thematic Analysis

An inductive thematic analysis approach was employed to analyze the qualitative data, drawing on the methodological principles outlined by [Braun and Clarke \(2006\)](#). The expanded field records and interview notes were reviewed repeatedly to ensure deep familiarity with the participants’ narratives. All 12 interviews were conducted by the researcher, who also independently reviewed and coded the handwritten field notes. Neither participant member checking nor peer debriefing was conducted. The interviews were not audio-recorded or transcribed verbatim. Handwritten interview notes were originally prepared in Bengali, and the relevant content was subsequently translated into English during the thematic interpretation and preparation of the manuscript. The English-language findings therefore represent thematic summaries and paraphrased accounts rather than verbatim translations of individual participant statements. Meaningful segments of the text were initially assigned open, descriptive codes directly from the raw data without imposing predetermined categories. These codes were then iteratively grouped into broader conceptual categories based on recurring patterns and shared experiences across the 12 participants. For example, difficulties in retrieving previously received

SMS advisories were represented by the descriptive code “difficulty retrieving SMS messages,” grouped under the category “information accessibility and retrieval,” and associated with the broader theme of barriers to information retrievability. This process resulted in the identification of six primary themes: (1) the need for context-specific and crop-specific information; (2) the information requirements of diversified livelihoods; (3) the role of broader land-use tradeoffs; (4) barriers to information retrievability; (5) challenges related to digital literacy; and (6) a farmer preference for hybrid information systems. These themes were identified before the development of the proposed BP-CAAF design framework. Following the thematic analysis, the framework was conceptualized by integrating the identified information needs with relevant literature on climate information services, co-production, and participatory sensing. Thus, the identification of interview themes was inductive, whereas the subsequent framework development was theoretically informed.

3.5. *Researcher Positionality and Ethical Considerations*

The researcher is originally from Sherpur, Bangladesh, and possesses deep familiarity with the language, agricultural practices, and socio-cultural nuances of the study region. This insider perspective facilitated rapid rapport-building, created a comfortable interview atmosphere, and enabled participants to articulate their experiences freely in their colloquial Bengali dialect. However, such familiarity can inadvertently introduce interpretive assumptions or preconceptions during data analysis. To mitigate this risk, data analysis followed a disciplined iterative protocol: codes and emerging categories were continually cross-referenced against the raw narrative accounts in the expanded field notes, ensuring that the finalized themes faithfully reflected the farmers’ lived experiences rather than pre-existing researcher expectations.

This study was conducted as an independent research project. Verbal informed consent was obtained from all participants before the interviews, and consent was documented in the researcher’s handwritten field records. Formal institutional ethical approval was not obtained before data collection because the researcher’s institution did not have a standing ethics review board for non-clinical social science research at the time of fieldwork. The absence of formal institutional ethical review is acknowledged as a limitation of the study. The study followed general ethical principles for social science research, including voluntary participation, informed consent, respect for participants’ autonomy, and protection of confidential information. Participants’ names and the identities of the study villages have been withheld from the manuscript to reduce the risk of identification.

4. Findings

4.1. *Farmers Have Different Climate Information Needs Depending on What They Produce*

As shown in Table 2, the 12 participants cultivated a range of crops, including rice, potatoes, vegetables, mustard, and jute, reflecting differences in their agricultural activities and associated information needs. This variation is important because the usefulness of climate information depends on what the farmer is producing and at what stage of production.

For illustration, a forecast of heavy rainfall may have different implications for paddy cultivation than for vegetable production, depending on the crop and its stage of growth. Similarly, the implications of a forecast may differ between planting, vegetative growth, flowering, and harvesting periods.

This suggests that farmers may benefit more from information that connects a forecast to a specific agricultural context. Rather than simply communicating that rainfall or temperature is expected to change, a message could explain the potential implications for a particular crop or farming activity.

A further concern raised during the interviews was the limited geographical specificity of climate advisories. District-level forecasts or advisories may not adequately reflect weather conditions experienced at individual farm locations. Anecdotal accounts from the local farming context, rather than documented participant interviews, further illustrate how geographically broad rainfall forecasts may not reflect conditions at individual farms, potentially affecting decisions about the timing of agricultural activities.

4.2. *Climate Information Needs Extend Beyond Crop Farming*

Seven of the twelve participants reported engaging in fish farming alongside crop production. These mixed farming systems create additional information needs because weather and environmental conditions can affect crops and fish production differently.

For farmers managing both activities, climate information may need to address issues such as excessive rainfall, flooding, water levels, temperature, and other conditions relevant to both crop fields and fish ponds. The same climate event may create a risk for one activity while creating a different management issue for another.

This finding indicates that a climate information service designed solely around crop production may not fully reflect the livelihood decisions of diversified farming households.

4.3. Land Leasing for Brick Production Creates a Different Type of Livelihood Decision

Two of the twelve participants mentioned leasing agricultural land to brick producers as a means of generating income, although their individual participant IDs were not systematically recorded in relation to this practice. This decision differs from conventional farm-level responses such as changing planting dates or crop varieties. It represents a broader livelihood and land-use decision in which immediate financial returns may be weighed against longer-term agricultural considerations.

Existing literature and anecdotal observations suggest that using agricultural land for brick production may raise concerns about soil fertility and future agricultural productivity. However, the present interviews did not systematically investigate or independently verify these environmental effects.

The reported land-leasing practices highlight the broader livelihood decisions faced by some farmers. Although the interviews did not establish a relationship between climate information and these land-use decisions, they suggest that agricultural information services could potentially address a wider range of livelihood considerations beyond immediate crop management.

4.4. Receiving Information Does Not Mean Being Able to Retrieve It

A major concern among participants was the difficulty of tracking information received through SMS. Although SMS does not require a smartphone or internet connection, farmers reported that messages could become difficult to find after receiving additional messages. This creates a problem when information needs to be consulted later to make an agricultural decision.

For example, several farmers reported that finding older messages was difficult or inconvenient. One participant explained that information could be useful when initially received but less useful later if the farmer could not easily locate the message again.

This finding suggests that delivery alone is an incomplete measure of access. A farmer may technically receive a climate warning but still be unable to use it at the moment a decision must be made. Climate information therefore needs to be not only timely but also retrievable.

4.5. Smartphone Applications May Create a Digital-Literacy Barrier

Participants also identified limitations associated with smartphone applications. Although apps can provide more detailed and frequently updated information than SMS, they require smartphones and a certain level of digital literacy.

Among the 12 farmers interviewed, 6 reported owning smartphones, while the remaining 6 primarily relied on basic mobile phones. Even among smartphone owners, 3 participants reported difficulty navigating agricultural or weather applications.

These findings indicate that smartphone-based climate services may not be equally accessible to all farmers. Older farmers or farmers with less experience using digital technologies may find applications more difficult to navigate. Limited connectivity and data costs may also reduce the practical usefulness of app-based services.

4.6. Farmers Could Benefit From a Hybrid Information System

Rather than rejecting digital technology, participants generally expressed interest in combining digital information with simpler offline communication. Nine of the 12 farmers indicated that they would prefer receiving concise digital alerts alongside periodic summaries or explanations through offline channels.

A potential model could include short SMS or voice alerts for urgent information, followed by a weekly or biweekly summary tailored, where possible, to the crops or farming activities of the recipient. The summary could be distributed through agricultural extension workers, local meetings, printed materials, or other community-based channels. This approach could address two different problems. Digital alerts would allow information to reach farmers quickly, while offline summaries would make it easier to understand and retain information. Local agricultural workers could also help translate forecasts into practical recommendations relevant to specific crops, varieties, fish farming activities, or stages of production.

5. The Bidirectional Participatory Climate-Agro Advisory Framework (BP-CAAF)

To address the limitations identified in the interviews, this study proposes the Bidirectional Participatory Climate-Agro Advisory Framework (BP-CAAF). The framework is a conceptual proposal informed by the identified information needs and relevant literature; the interviews did not assess farmers' willingness or ability to participate in the proposed feedback and crowdsourcing mechanisms. This framework is designed to restructure the conventional, linear broadcast pipeline by modeling the advisory ecosystem as a closed-loop, socio-technical system. It pairs the top-down process of data downscaling and localization with a bottom-up, crowdsourced flow of participatory sensing and evaluation. The central proposal is the transformation of smallholders from passive recipients of information into active, distributed nodes within the sensing and validation infrastructure.

5.1. System Architecture and Functional Tiers

The BP-CAAF is organized into three interconnected operational tiers, which manage the flow of data from national-level forecasting to farm-level execution and back. Figure 1 provides a schematic overview of this architecture.

- **Tier 1: Macro-Level (Policy and Science).** Ingests national and global data (e.g., Numerical Weather Prediction models, satellite imagery) from institutions such as the Bangladesh Meteorological Department (BMD). This tier provides the foundational, coarse-grid scientific forecasts.
- **Tier 2: Meso-Level (Processing and Localization).** Acts as the central processing engine. It fuses macro-forecasts with local datasets (e.g., soil maps, crop calendars) and, crucially, processes incoming farmer feedback. It houses a Spatial Consensus and Outlier Rejection Engine to validate crowdsourced data and generate tailored, micro-level advisories. Regional agricultural extension officers support the interpretation and localization of climate advisories and coordinate with field-level agricultural extension agents.
- **Tier 3: Micro-Level (Execution and Participatory Sensing).** Represents the field-level environment of smallholder farmers. It includes dual-mode delivery channels (e.g., simplified smartphone apps and interactive SMS/IVR) and intuitive upward sensing channels for farmers to log observations and rate advisories. On-field agricultural extension agents help communicate localized advisories to farmers and facilitate the collection of local observations and feedback for transmission to Tier 2.

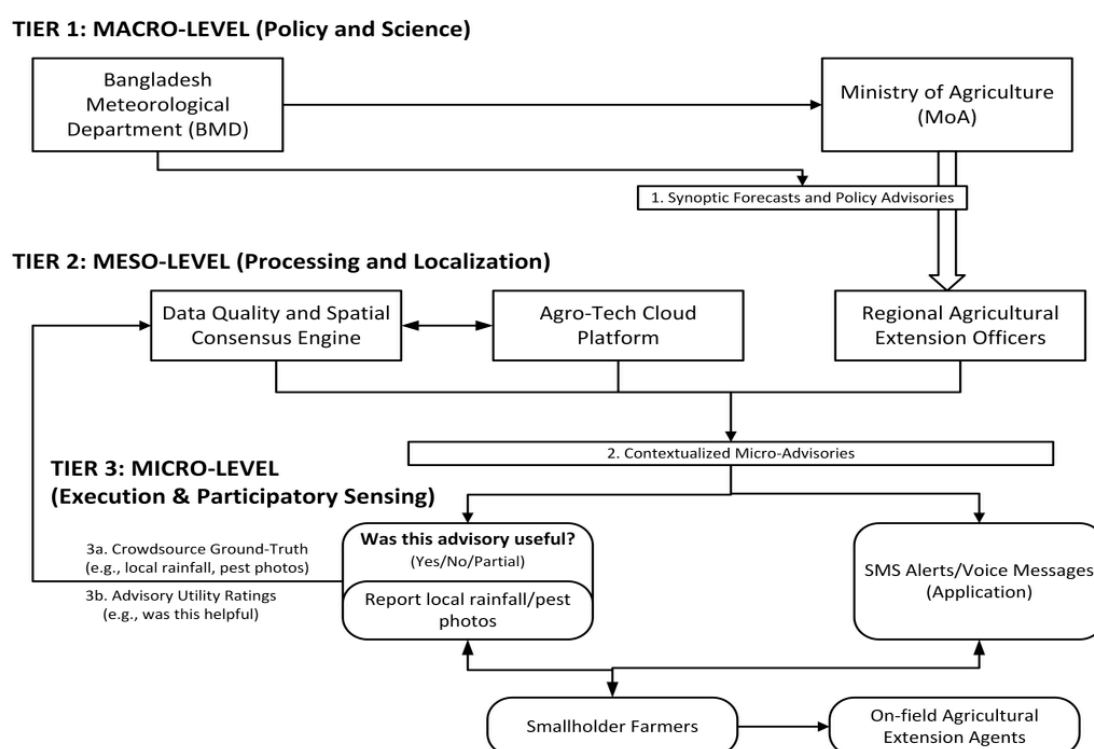


Figure 1: Architectural Schematic of the Bidirectional Participatory Climate-Agro Advisory Framework (BP-CAAF), Showing Multi-Tier Data Workflows and Upward Validation Feedback Loops

Source: Author's conceptualization.

5.2. The Dual Crowdsourced Feedback Loops

The operational core of the BP-CAAF lies in its two distinct, upward participatory feedback mechanisms. These loops transform a one-way broadcast into a dynamic, self-correcting learning system.

Feedback Loop 1: Physical Ground-Truth Verification

To validate and downscale coarse meteorological forecasts, this loop enables smallholders to contribute simple, structured observations of physical ground conditions. This includes binary reports on rainfall occurrence (“Did rain fall on your field today?”), the presence of pests or diseases (via image capture or icon menus), and key phenological milestones (such as flowering or harvest readiness). This stream of objective physical data allows the meso-level engine to detect local variations that coarse satellite grids would miss, thereby correcting model biases and improving the accuracy of localized forecasts. The system is designed such that when a threshold number of farmers report similar pest anomalies, the platform triggers a localized warning.

Feedback Loop 2: Advisory Utility and Actionability Ratings

To evaluate whether advisories are clear, timely, and practical, the system collects structured subjective feedback after an alert is issued. Within 24 to 72 hours, the platform can deliver a brief prompt asking if the advisory was useful or if it arrived in time to adjust work. If an advisory is marked as unhelpful, a simple follow-up can capture the reason (e.g., “Input Unavailable,” “Wrong Crop Stage,” or “Weather Did Not Match”). By aggregating these utility ratings, the meso-level engine can learn which types of advice are genuinely actionable under real-world rural constraints, allowing for iterative refinement of advisory language, thresholds, and delivery timing.

5.3. Ensuring Data Quality: Spatial Consensus and Outlier Rejection

A significant challenge in any participatory sensing system is ensuring data quality, as unintentional user errors or false reports can pollute the system. To address the challenge of data quality, a potential implementation of BP-CAAF could incorporate a spatial consensus filter at the meso-level. Before using crowdsourced data to update local models, the engine applies a validation process. It requires a minimum number of independent reports from a given geographic grid cell to trigger a correction. Furthermore, it calculates a weighted consensus among these reports, giving more influence to farmers who have a history of reliable reporting.

This automated check is intended to prevent individual errors from corrupting the advisory pipeline. For example, if a sufficient number of trusted farmers in a specific area report an unpredicted rainfall event, the system can register a likely local micro-climate anomaly and recalibrate forecasts for that zone. Conversely, a single, anomalous report that diverges from the consensus is flagged as a likely outlier and is given a lower weight, thereby maintaining the integrity of the overall system. This mechanism allows the framework to harness the power of local observation while reducing the risk of data pollution.

It is important to emphasize that BP-CAAF is presented here as a conceptual design framework informed by the qualitative findings and relevant literature; its empirical validation through field pilots remains a crucial next step for future research. The practical implementation of BP-CAAF would require further assessment of technical, social, and institutional feasibility. Weighting farmer reports according to previous reporting reliability could disadvantage new participants or those with limited digital literacy. Given the varying levels of digital proficiency and mobile-phone access identified in this study, alternative reporting channels, such as SMS, voice communication, or assistance from agricultural extension workers, would be necessary to support inclusive participation. Additional considerations include informed consent, data privacy and protection, incentives for sustained participation, implementation and maintenance costs, and clearly defined institutional responsibilities among relevant agencies and service providers. These issues remain unresolved design considerations requiring evaluation before practical implementation.

6. Discussion

The study’s findings highlight a central challenge: the problem with digital climate information is not simply access but contextualized usability and actionability. A climate message may reach a farmer’s phone yet still fail to provide relevant information for the farmer’s specific crop, activity, or livelihood decision. This suggests a mismatch between centralized climate science and local agricultural practice, to which the BP-CAAF framework is intended as a response.

6.1. From One-Size-Fits-All to Contextualized Decision Support

Participants reported a diversity of crops and production stages. This suggests that a single advisory approach is insufficient: a generic forecast of heavy rainfall may carry different operational implications depending on a farmer’s specific

crop, farming sub-sector, or growth-cycle stage. Climate information systems should therefore move beyond broadcasting generic forecasts toward decision support that considers the forecast, the activity, and the timing of the decision.

These findings are consistent with Warner et al. (2022), who identify accessibility, communication, and institutional factors as important influences on the use of agricultural climate information. They also complement Kumar et al. (2021), whose research in the Lower Bengal Delta highlights the value of combining digital forecasts with face-to-face communication and farmer capacity building. The present study adds an exploratory perspective by highlighting differences in information needs across crops, mixed farming activities, and farmers' digital capabilities, while also identifying difficulties in retrieving previously received SMS advisories.

This need for context becomes more complex with mixed farming. Farmers who combine crop production with fish farming need information for their entire livelihood portfolio. The BP-CAAF's localization tier is intended to address this problem by tracking farm profiles, including integrated fishponds, so that the system can generate joint advice that helps farmers navigate the trade-offs in their diversified operations.

6.2. Bridging the Knowledge Divide and Building Trust

Conventional advisory systems tend to position central agencies as the main source of authoritative knowledge, which may undermine trust when forecasts prove wrong. The BP-CAAF challenges this model by formally recognizing smallholders as expert observers of their own environments and allowing farmers to contribute local observations, which may help bridge the knowledge divide between institutional science and local experience.

This two-way flow also changes the meaning of a forecast error. In the proposed system, an inaccurate advisory becomes an opportunity for improvement. A farmer can report that a predicted storm did not occur; this becomes a valuable data point for the system rather than merely a complaint. The farmer becomes an active participant in improving the service, rather than a passive victim of a bad forecast, and this process may build trust through transparency and collaboration.

This approach aligns with established findings in the climate services literature, which show that trust is built not only on raw forecast accuracy but also on institutional transparency, user agency, perceived legitimacy, and service credibility (Carr et al., 2020; Cash et al., 2003; Vaughan & Dessai, 2014).

6.3. Implications for Service and Policy Design

The findings suggest several practical directions. First, digital messages must be short, clear, and actionable. They must also be context-specific, distinguishing between major crops and farming activities. Second, digital services should offer multiple formats. SMS can provide fast alerts. Voice messages and simple offline materials can improve accessibility.

Third, policymakers should develop hybrid digital–offline systems. These systems can combine the speed of digital tools with the contextual support of local extension agents. Intermediaries can help translate general forecasts into specific advice. They can also make information easier to understand and remember. Finally, programs should recognize that farmers make broader land-use decisions. Climate services alone cannot resolve these complex trade-offs. They can, however, be part of a larger system of agricultural and environmental information. To achieve this, policy frameworks must adopt performance metrics that go beyond simple delivery rates. Three specific, measurable indicators aligned with the principles of the proposed framework are suggested:

- I. Advisory actionability rate: measuring the percentage of digital advisories that farmers self-report as directly applicable to a specific crop management or livelihood decision.
- II. Decision uptake: monitoring the rate at which farmers actively adopt recommendations (e.g., altering planting dates or applying pest controls) in response to received messages.
- III. Forecast–outcome discordance reporting: tracking the frequency and spatial distribution of discrepancies between system forecasts and farmer-observed microclimates to feed back into service refinement.

7. Conclusion

This study suggests that the ongoing vulnerability of smallholder farmers in Bangladesh is not due solely to a lack of climate data but may be rooted in a one-way information architecture. Such a system treats farmers as passive consumers of coarse, uncalibrated forecasts. When advisories fail to account for local micro-climates, ignore mixed farming systems, and arrive through cluttered channels, farmers may understandably disregard them.

The Bidirectional Participatory Climate-Agro Advisory Framework (BP-CAAF) offers a potential alternative. It proposes a multi-tiered network that combines scientific forecasts with crowdsourced ground-truthing, which would transform

agricultural advisory delivery into a closed-loop, self-correcting system. The framework's primary contribution is its recognition of farmers as active participants. It views them not as aid recipients but as knowledgeable partners in building climate resilience.

This study has several limitations that should be acknowledged. First, the findings are based on a small, purposively selected sample (N = 12) within a single district in Bangladesh, meaning the results are exploratory and illustrative rather than statistically generalizable across different agro-ecological zones. Second, the sample was exclusively male, meaning that the study did not capture women's perspectives on agricultural practices, digital access, and climate information needs; future research should prioritize gender-balanced samples to capture distinct gendered climate information needs. Finally, this cross-sectional study offers a temporal snapshot; longitudinal research is necessary to evaluate the long-term usability and real-world impacts of the proposed BP-CAAF design framework.

Additionally, the reliance on handwritten interview notes rather than audio recordings or verbatim transcripts may have resulted in the loss of contextual details and nuances of participants' expressions. The thematic translation of Bengali field notes into English during manuscript preparation may have introduced further interpretive limitations. Consequently, the study cannot provide independently verifiable verbatim participant quotations. The interviews and thematic analysis were conducted by a single researcher. Neither participant member checking nor peer debriefing was undertaken to independently assess the interpretation of the findings. The absence of these procedures may have increased the potential for researcher subjectivity and limited opportunities to assess the credibility of the identified themes. Furthermore, the findings rely primarily on participants' self-reported experiences, which were not independently verified. The sample was drawn from only two villages within a single district, further limiting the transferability of the findings to other agricultural communities.

Despite these limitations, this study argues for a crucial departure from traditional, top-down extension models. By centering the lived realities of smallholder farmers managing complex livelihoods, it suggests that the path to effective climate resilience lies not in digitalization alone, but in co-producing contextualized and actionable knowledge. The more important goal is to make information accessible, understandable, and directly relevant to farmers' decisions. Shifting from a linear broadcast to a bidirectional, participatory model (as conceptualized in the BP-CAAF framework) is an essential step toward building such adaptive and trustworthy systems. Ultimately, empowering rural communities with a voice in the information value chain is fundamental to securing sustainable livelihoods in an increasingly unpredictable climate.

Declarations

Declaration of Generative AI in the Writing Process

The author used ChatGPT (version 6, OpenAI) and Gemini (version 2.5, Google) to assist with language editing, grammatical corrections, and improvements to the clarity and organization of the manuscript. The author reviewed and revised the AI-assisted text and takes full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflict of Interest

The author declares no conflict of interest.

Data Availability Statement

The handwritten interview notes supporting the findings of this study are available from the corresponding author upon reasonable request, subject to appropriate anonymization and confidentiality safeguards to protect participants' identities.

Ethics Approval

Participants provided verbal informed consent after being informed of the study's purpose and the voluntary nature of participation. Consent was documented in handwritten field notes. Formal institutional ethics approval was not obtained because the institution did not have a standing ethics review board for non-clinical social science research at the time of fieldwork. This limitation is acknowledged in the manuscript.

Author Contributions

The sole author was responsible for the study conception and design, data collection, analysis and interpretation, manuscript preparation, and final approval of the submitted version.

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Appendix A

Retrospective Summary of Interview Topics

This appendix presents a retrospective summary of the main topics covered during interviews with smallholder farmers. The summary is based on the researcher's recollection of the interview discussions and does not reproduce the original interview guide verbatim. The topics are organized thematically rather than in the sequence in which they were discussed.

Agricultural Land and Farming Practices

- Amount of agricultural land cultivated by the participant.
- Whether the participant was actively engaged in farming.
- Types of crops cultivated by the participant.
- Whether participants cultivated rice once or twice annually on the same agricultural land, particularly during the Boro and Aman growing seasons.
- Whether participants cultivated crops other than rice.
- Reasons for leasing agricultural land to brick producers.
- Whether the participant engaged in fish farming.

Crop Selection and Diversification

- Reasons for cultivating crops other than rice.
- Factors influencing decisions to switch from rice cultivation to other crops.

Crop Management and Agricultural Challenges

- Challenges encountered in maintaining crop health.
- Crop-specific cultivation and management requirements.
- Precautionary measures taken before the onset of flood-prone or dry seasons.

Access to Agricultural Information and Digital Technology

- Familiarity with and comfort using smartphone applications.
- Preferences for obtaining agricultural information through in-person agricultural extension agents versus automated digital information services.
- Perceived ease of accessing and understanding agricultural information through these different channels.
- Whether farmers received information about anticipated floods or dry conditions in time to take preventive action, and reasons for delays or lack of access.