



RESEARCH ARTICLE

The role of indigenous knowledge and local wisdom in climate adaptation : Forest farmers group in Buton, Southeast Sulawesi, Indonesia

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Abstract

Climate change poses significant threats to smallholder farming systems, yet limited research has examined how indigenous knowledge and local wisdom shape adaptive responses in varied agroecological contexts. This study addresses this gap by analysing climate adaptation strategies among smallholder farmers in Buton Regency, Southeast Sulawesi, across upland (Kapontori), midland (South Lasalimu) and lowland (Siotapina) zones. Data were collected from 250 randomly selected forest-farmer households through household surveys, key informant interviews and focus group discussions, supported by thematic and descriptive statistical analyses. While descriptive patterns suggest spatial contrasts such as stronger reliance on experiential knowledge in Kapontori and a greater role of peer networks in South Lasalimu and Siotapina, Chi-square tests revealed that differences in information sources and climate perceptions across the three zones were not statistically significant ($p > 0.05$), indicating convergence rather than divergence in farmers' climate knowledge systems. However, variation in adaptation practices remains evident; for instance, rainwater harvesting shows lower uptake in Kapontori (44 %) compared to South Lasalimu (80 %) and Siotapina (75 %), reflecting differences in water availability and perceived urgency. Recommendations include embedding indigenous knowledge into formal climate advisory services, strengthening farmer-to-farmer knowledge exchange and investing in context-specific technologies. Theoretically, the study reinforces the co-production of knowledge framework, demonstrating that resilience is enhanced when traditional wisdom and modern innovations are integrated through local institutions.

Keywords: agricultural resilience; climate change adaptation; local knowledge; rural Indonesia; smallholder farmers

Introduction

Climate change has been widely acknowledged as a key driver of declining agricultural productivity, heightened food insecurity, job losses, depletion of natural resources and intensifying competition over resource use (1–5). As the risks associated with extreme weather events increasingly threaten agricultural livelihoods, research into the impacts of climate change on agriculture and rural communities has become a critical area of inquiry (6–8). Smallholder farmers, face growing vulnerability due to rising temperatures, erratic rainfall patterns and the increased frequency of floods and droughts. These vulnerabilities are often exacerbated by systemic issues such as poverty, low technological adoption, political instability and the heavy reliance on climate-sensitive sectors like agriculture and forestry (9).

In Indonesia, a country highly dependent on agriculture, climate change has significantly disrupted rural livelihoods. The nation ranks among the most climate-vulnerable globally, especially to hydrometeorological hazards like floods and droughts that compromise agricultural productivity and food security (10–12). Marginalised communities with limited economic assets tend to suffer disproportionately from climate-related shocks, which can

further entrench poverty and social vulnerability (13, 14). In rural areas, particularly among forest-adjacent populations, farmers typically rely on subsistence agriculture, possess minimal formal education and depend heavily on family labor and natural resources for their livelihoods (15). Depending on traditional farming methods, lack of irrigation infrastructure and limited access to innovation have compounded the socio-economic challenges faced by these communities, widening the development gap and undermining the long-term sustainability of livelihoods. Thus, identifying effective strategies to enhance the adaptive capacity of farmers in climate-affected regions is an urgent priority (16).

Farmers in many developing countries face increasing risks of yield loss due to climate variability and the absence of adaptation strategies is expected to intensify these challenges (17). Reliance on predictable seasonal cycles makes indigenous farmers particularly vulnerable to climate anomalies, requiring proactive adaptation to maintain agricultural productivity (18). In regions such as Sukoharjo and Klaten, where livelihoods are almost entirely dependent on agriculture, the risks posed by climate change are acute (19). Similarly, in Sub-Saharan Africa, overdependence on rain-fed agriculture has made farming systems highly susceptible to climate variability (20, 21). Despite the growing recognition of these issues,

there remains a limited understanding of how smallholder farmers perceive seasonal changes and respond to climatic shifts in terms of agricultural practices and decision-making.

Southeast Sulawesi, Indonesia, characterised by rich ethnic diversity, is one of the regions most exposed to climate risks, particularly flooding driven by upstream deforestation (22). Although numerous studies have assessed livelihood vulnerability in various contexts, many emphasise structural determinants such as household characteristics, infrastructure availability, technological access, livelihood diversification and financial inclusion (23–26). However, few have examined how local farmers comprehend and identify climate change characteristics within different ecological settings namely upland (Kapotori), midland (Lasalimu Selatan) and lowland (Siotapina) zones. A deeper understanding of farmers' knowledge is essential to navigate the complexity of climate variability and to tailor effective adaptation interventions.

This study aims to address this gap by analysing local and indigenous knowledge regarding climate change and how it influences adaptation strategies in their livelihood systems. The study focuses on subsistence farmers who, while cultivating their own produce, often do not own the land they work on a factor that further contributes to livelihood vulnerability. By assessing the level of knowledge and corresponding adaptive behavior, this research seeks to inform appropriate interventions that enhance climate resilience. Ultimately, the findings are expected to guide development programs in designing context-sensitive approaches to strengthening the adaptive capacity of smallholder farmers in climate-exposed areas.

Local or indigenous knowledge systems serve a pivotal role in enhancing the climate resilience of smallholder farmers. In the absence of modern technological tools, these farmers rely on environmental cues such as the behavior of plants, wind patterns and other localised phenomena to anticipate the onset of rainy seasons and potential climate-related threats like droughts. Indigenous knowledge is transmitted through multiple pathways, including personal experience, generational inheritance, community interactions and particularly the wisdom of elders. Smallholder farmers employ a variety of adaptation measures rooted in indigenous practices, such as intercropping, crop diversification, traditional water conservation methods (e.g., local dams), spiritual practices, alternative livelihood strategies, entrepreneurial engagement and the application of locally produced bio-pesticides (27, 28). The use of indigenous and local knowledge for weather and climate forecasting significantly enhances farmers' situational awareness and preparedness. In regions like Chiredzi in south-eastern Zimbabwe, smallholder farmers heavily depend on these knowledge systems to forecast both short-term and seasonal rainfall, which informs their agricultural planning and decision-making processes (29–31).

The integration of indigenous knowledge (IK) and local institutions (LI) forms a critical theoretical framework in shaping smallholder farmers' adaptive responses to climate change. Strong IK systems provide experiential, place-based understanding of environmental patterns, while well-functioning local institutions serve as channels for collective learning, resource coordination and information dissemination. Together, they facilitate the co-production of knowledge and promote the adoption of climate-smart agricultural innovations. The effectiveness of adaptation practices is closely linked to the strength of these systems: when

both IK and LI are robust, farmers are more likely to trust and implement adaptive measures that are contextually relevant, culturally accepted and ecologically sustainable. This synergistic relationship enhances resilience by aligning traditional coping strategies with modern adaptation techniques, especially in rural settings where institutional support is limited and climate variability is high (32).

This study adopts a co-production of knowledge framework to examine how smallholder farmers combine indigenous knowledge, local experience and socially shared information in responding to climate variability. The framework emphasises that climate adaptation knowledge is not generated solely through formal scientific institutions, but is collectively shaped through interactions among farmers, local institutions, community networks and environmental observations. In this study, the framework guided the exploration of how farmers interpret climatic signals, exchange adaptation practices and integrate experiential knowledge into agricultural decision-making across different agroecological zones. The mixed-methods approach was therefore designed to capture both quantitative adaptation patterns and the socio-cultural processes underlying local climate knowledge production.

Materials and Methods

Description of study area

This research was conducted in Buton Regency, Southeast Sulawesi, which has varying altitudes from coastal areas (0 m above sea level) to hilly and mountainous areas with an altitude of 0–808 m above sea level (upland) in Kapontori District, 0–462 m above sea level (midland) and 0–346 m above sea level in South Lasalimu District (lowland) (Fig. 1) (33). The climate of the area is influenced by humidity from the Pacific Ocean, which brings dry winds causing the dry season and the Indian Ocean, which is the source of southwest monsoon winds that bring moist air masses, causing the rainy season. Mixed agriculture and plantations are the main livelihoods in the area and are among the most vulnerable areas to climate change and variability in Indonesia.

Data collection and analysis

This study was conducted in three sub-districts of Buton Regency, Southeast Sulawesi, strategically selected to represent upland, midland and lowland agroecological zones. These locations were chosen purposively to capture the diversity of topographic and ecological conditions affecting local farming systems. Data collection involved a mixed-methods approach, combining household surveys of forest farmer groups, key informant interviews conducted in local languages to enhance clarity and engagement and focus group discussions (FGDs) held in each sub-district. In the preliminary phase, consultations were held with agricultural extension personnel from Kapontori, Siotapina and Lasalimu Selatan to ensure a representative sampling framework that reflects the region's agroecological variation. Selection criteria included exposure to climate extremes, natural disaster frequency, incidences of crop failure, crop rotation patterns and the prevalence of indigenous weather forecasting practices.

These areas also experience challenges such as food insecurity, land degradation, declining soil fertility and subsistence-level productivity, all contributing factors to rural poverty. In addition to descriptive statistics, a Chi-square test using SPSS of

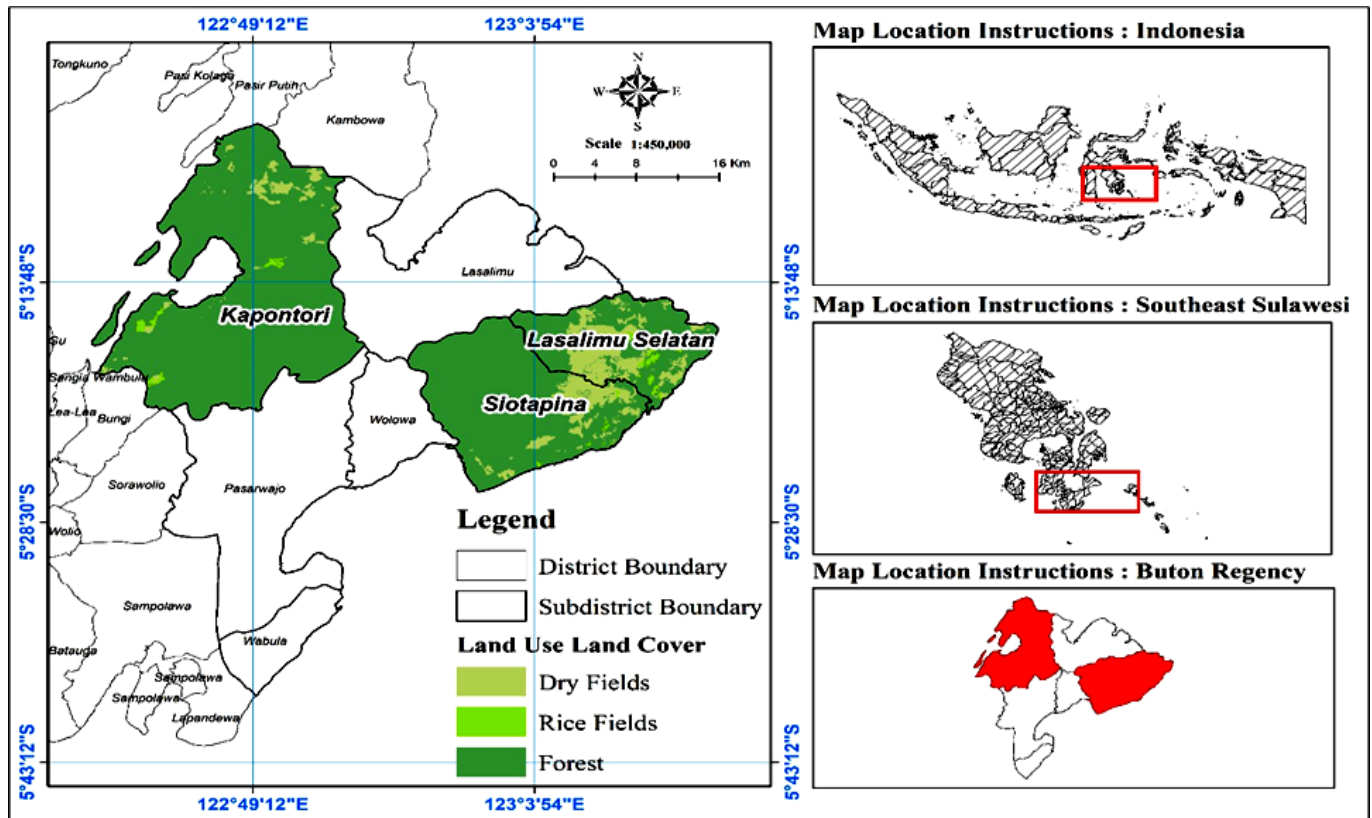


Fig. 1. Location of the study area.

independence was employed to assess whether differences in adaptation strategies and information sources were statistically associated with agroecological location. This inferential test enabled verification of whether observed variation across Kapontori, South Lasalimu and Siotapina reflect meaningful geographic patterns rather than random distribution.

Chi-square tests were conducted at the household level using a total sample of 250 respondents to examine associations between agroecological location and categorical adaptation-related variables. The tested variables included farmers' sources of weather and climate information, perceived characteristics of climate change and selected adaptation strategies across upland (Kapontori), midland (South Lasalimu) and lowland (Siotapina) areas. All variables were coded categorically based on household survey responses and statistical significance was evaluated at the 5 % level ($p < 0.05$). The analysis was intended to determine whether observed differences among locations reflected statistically significant variation rather than descriptive percentage differences alone.

A multistage sampling technique was employed to ensure representation across different agroecological zones in Buton Regency. In the first stage, three agroecological areas representing upland (Kapontori), midland (South Lasalimu) and lowland (Siotapina) conditions were purposively selected based on differences in elevation, farming systems and climate exposure. In the second stage, active forest farmer groups within each area were identified in consultation with local agricultural offices and community leaders. In the final stage, respondent households were randomly selected from farmer-group membership lists, resulting in a total sample of 250 farming households. The FGD participants were identified purposively by local extension agents and respected community leaders based on their demonstrated knowledge of climate change and local adaptation practices. The qualitative data collected included observations on environmental indicators, traditional weather forecast signals, extreme climate events and the

application of such knowledge in agricultural decision-making. Following previous research, a thematic analysis approach was applied to analyse data from interviews and FGDs, which is particularly suitable for handling large volumes of qualitative information (34). Quantitative data from household surveys were analysed using descriptive statistical methods to complement and triangulate the findings.

Results

Background of respondents

The socio-economic profile of farmers in Kapontori, South Lasalimu and Siotapina illustrates clear variations in demographic attributes, resource endowments and livelihood strategies, all of which influence adaptive capacity to climate change in Buton Regency. Farmers are predominantly in their mid-40s to mid-50s, with only elementary education, indicating potential limitations in accessing and applying climate-smart agricultural innovations. South Lasalimu farmers possess the longest farming experience and the highest income, suggesting stronger economic resilience, while Kapontori farmers cultivate the largest land area and maintain the greatest water reserves, reflecting higher resource availability for adaptation. Conversely, Siotapina's smaller landholdings and lower water reserves may heighten vulnerability. Crop diversity differs across sites, with each sub-district tailoring production to local agroecological conditions ranging from rice and vegetables in Kapontori, root crops and leafy greens in South Lasalimu, to mixed staples and fruit crops in Siotapina demonstrating localised adaptation strategies. These differences align with findings from earlier reports, which emphasise that education level, farming experience, landholding size and access to resources critically shape farmers' perceptions, decision-making and resilience in the face of climate variability (35–37) (Table 1).

Table 1. Background information of respondents

Item	Kapontori	South Lasalimu	Siotapina
Average age (in years)	49	56	46
Education level	Elementary School	Elementary School	Elementary School
Average family size	5	6	5
Average farming experience (in years)	15.27	24.17	19.15
Average land area (m ²)	1,841.56	558.07	335.52
Average income (IDR)	594,800	1,391,018	1,116,959
Average rice reserves (kg)	26.19	58.33	33.75
Average water reserves (liters)	464.86	375.5	289.85
Types of commodities planted	Rice, Patchouli, Green Beans, Eggplant, Cabbage, Chili Peppers, Pumpkin, Corn, etc.	Moringa, Eggplant, Chili, Cassava, Mustard Greens, Spinach, Rice, Patchouli, Corn etc.	Rice, Corn, Patchouli, Beans, Eggplant, Chili, Banana, etc.

Chi-square test results (Table 2) indicate that geographical variation across the upland, midland and lowland zones does not significantly influence farmers' sources of weather and climate information or their perceived characteristics of climate change (Pearson $\chi^2 = 6.000$, $df = 4$, $p = 0.199$). Given that the p -value exceeds the 0.1 threshold, the observed differences across locations were descriptive rather than statistically significant. This suggests that farmers' access to information channels and their experiential recognition of climate-related phenomena are broadly consistent across agroecological settings, implying that shared livelihood systems and exposure to similar climatic stressors may outweigh the effects of topographic differentiation.

Table 2. Chi-square tests

Chi-Square Tests			
	Value	Df	Asymptotic significance (2-sided)
Pearson Chi-square	6.000	4	0.199
Likelihood ratio	6.592	4	0.159
N of valid cases	3		

Farmers' sources of weather and climate information

Farmers' sources of climate information (Table 3) are primarily derived from their own experiences by observing natural characteristics such as wind patterns, monsoonal transitions and the movement of clouds. Some farmers also obtain weather and rainfall information from mass media, particularly updates from the local Meteorology, Climatology and Geophysics Agency (BMKG) Pasarwajo. Information sharing among farmers often occurs during discussions at monthly member meetings. As shown in Table 3, agricultural extension services are a rare source of information, largely because the number of extension officers in Buton Regency is very limited relative to the vast area they must cover. An agricultural extension officer in Kapontori Sub-district reported that they themselves rarely receive training or capacity-building support from the government, let alone organise climate-related training for farmers.

Consequently, farmers in Buton Regency exhibited low levels of climate literacy and have never participated in training specifically addressing the impacts of climate change on the agricultural sector. The extension services that are available tend to focus on crop cultivation techniques and the management of pests and plant diseases. Farmers in Kapontori reported receiving no weather- or climate-related information from agricultural extension officers. This absence of climate advisory support does not imply the absence of agricultural extension personnel; rather, it reflects a programmatic emphasis on agronomic practices, particularly crop cultivation techniques and pest and disease management. A similar pattern is observed in South Lasalimu and Siotapina, where only a small proportion of farmers indicated obtaining climate or weather information from local extension services, suggesting that climate communication remains peripheral within existing extension mandates.

The data indicate that farmers in Buton Regency rely on varying sources for weather information, with a predominance of traditional and experiential knowledge over formal channels. In Kapontori, 67 % of farmers depend primarily on their own experience, whereas South Lasalimu and Siotapina show higher reliance on interpersonal communication, with 25 % and 27 % respectively obtaining information from other farmers. Mass media plays a relatively minor role across all sub-districts (11–16 %) and formal mechanisms such as agricultural extension services remain minimal, particularly in Kapontori where no respondents reported using them. Notably, a significant proportion of farmers in South Lasalimu (34 %) and Siotapina (35 %) integrate multiple information sources, suggesting a more diversified approach to climate and weather awareness. These patterns reflect a strong reliance on indigenous knowledge systems and peer-to-peer learning, consistent with findings by previous researchers which highlight that in rural and resource-limited settings, farmers' adaptation to climate variability is often grounded in local experiential knowledge and informal networks, with limited uptake of institutionalised extension services (35, 38, 39). Strengthening the link between indigenous knowledge and formal weather advisory systems could enhance climate resilience in these communities.

Table 3. Source of weather and climate information

Farmers' weather information source	Kapontori	South Lasalimu	Siotapina
Mass media (television, internet, newspaper, social media)	15 %	16 %	11 %
Hearing from other farmers	18 %	25 %	27 %
Training and workshops	0 %	0 %	0 %
Agricultural extension	0 %	1 %	9 %
Own experience	67 %	24 %	19 %
a combination of two or more of these	0 %	34 %	35 %

Farmers' indigenous knowledge of climate change

Farmers in forest farming groups in Buton Regency recognise year-to-year environmental shifts that influence cultivation practices, yet they do not label these changes as climate change. Instead, through indigenous knowledge (Table 4), they describe altered rainfall timing, temperature variability and emerging pests and diseases using locally rooted ecological observations rather than scientific terms.

Table 4. Indigenous knowledge of climate change

Characteristics of climate change	Kapontori	South Lasalimu	Siotapina
Temperature changes	100 %	80 %	75 %
Changes in clothing styles	15 %	3 %	0 %
Animal migration	0 %	5 %	4 %
Extinction of certain species	87 %	18 %	43 %
Changes in visibility	0 %	2 %	2 %
Rainfall	85 %	70 %	75 %
Changes in rainy periods	54 %	69 %	66 %
Pest and plant disease outbreaks	97 %	88 %	76 %
Changes in cropping patterns	49 %	44 %	59 %
Decreased crop yields	79 %	86 %	87 %
Increased frequency of disasters	83 %	72 %	64 %

The most widely perceived indicator of climate change across all study sites is temperature change, reported by 100 % of farmers in Kapontori, 80 % in South Lasalimu and 75 % in Siotapina. Changes in rainfall patterns were also highly recognised, both in terms of overall rainfall reduction and shifts in rainy periods reported by over half of respondents in all areas. Pest and disease outbreaks were another dominant observation, affecting 97 % of farmers in Kapontori, 88 % in South Lasalimu and 76 % in Siotapina. Notably, decreased crop yields were reported by more than three-quarters of respondents across all sub-districts, with the highest in Siotapina (87 %). Increased disaster frequency, including floods and storms, was particularly recognized in Kapontori (83 %). Other indicators, such as extinction of certain species, animal migration and changes in cropping patterns, varied more wide among locations, reflecting differences in agroecological conditions and livelihood practices.

Qualitative data from farmer interviews and focus group discussions provide deeper insight into these perceptions. Respondents described a range of environmental cues that signal seasonal changes and extreme weather events. Soil cracking was considered a sign of the transition from rainy to dry season, while decreased water flow in fields indicated a seasonal shift. Phenological changes in sandalwood (*Santalum album* L.) leaf shedding for dry season onset and flowering for rainy season arrival were common reference points. Wind direction, particularly from west to east, was cited as a reliable indicator of the rainy season.

"The ground cracks when there's a climate shift from the rainy season to the dry season. If sandalwood trees shed their leaves, it means the dry season has arrived. However, if they sprout and flower, it's a sign of the rainy season"

Wildlife behaviour also served as a climate signal. South Lasalimu farmers noted increased sightings of monkeys and snakes in villages, while Siotapina farmers observed monkeys damaging crops. In Kapontori, the sudden disappearance of wild boars and other wildlife was linked to environmental stress. When climate change alters rainfall patterns, temperature and vegetation cover,

wildlife habitats in forests and surrounding ecosystems are degraded. In Buton's case, prolonged droughts, reduced water availability, loss of forest cover and loss of food plants in the wild can force animals like monkeys and snakes to move closer to human settlements in search of food and water. This pattern is documented in other climate-impacted regions. Previous researchers found that habitat loss and seasonal climate stress significantly increase human wildlife interactions, often resulting in crop damage and conflict (40, 41).

"Groups of monkeys always appear looking for food; in recent years, many monkeys have entered and destroyed farmers' crops; snakes often appear in the village"

Based on farmers' perceptions, the sudden mass die-off among wild boar and chickens is suspected to be due to prolonged drought. High temperatures can directly disrupt the physiology of both livestock and wild boar. This is also supported by previous researchers, whose extensive review documented how heat stress alters metabolism, gut integrity and disease susceptibility in chickens under warming conditions (42). Moreover, climate variability (changes in temperature and precipitation) can amplify the emergence and transmission of infectious agents by expanding vector ranges, altering host pathogen dynamics, or increasing environmental persistence of pathogens thereby precipitating sudden die-offs in both wild and domestic species. Recent syntheses and case studies highlight such climate-linked wildlife health threats and mass-mortality events.

Respondents reported that "What happened was that wild boars suddenly died out all at once last year, to the point where they're barely visible in the forest anymore; yes, that happened. Chickens suddenly died out"

Rainfall irregularities were described in detail, with farmers lamenting delayed season onset until late November or December, which disrupted traditional planting schedules. Pest pressures, including blue caterpillars, stem borers and Sclerotium wilt, were reported to have intensified in recent years, directly reducing yields of rice, patchouli and vegetables. Adaptation strategies have emerged in response to these changes, with farmers altering planting distances, modifying crop combinations and shifting planting dates. However, they also reported that extreme weather events, such as unexpected floods and droughts, frequently damage crops and reduce harvest potential. Heavy rains often destroy newly planted rice, while prolonged dry spells lower irrigation water availability. These findings are consistent with previous reports, which states that smallholder farmers in climate-sensitive regions rely heavily on indigenous ecological knowledge for agricultural decision-making yet face increasing challenges from climate variability that require the integration of traditional indicators with scientific forecasts to enhance resilience (35, 42, 43).

Forest farmer's group in Buton Regency demonstrated adaptive responses rooted in indigenous knowledge to cope with climate-induced stressors on agricultural production. Observed changes included widening planting distances from approximately 1 m to 2 m to enhance fruit development, intercropping high-value species such as patchouli between cassava rows and shifting from close-spacing to wider gaps to improve light penetration, reduce competition for water and accommodate additional crops. Temporal adjustments were also made, with planting schedules aligned more closely to the onset of the rainy season and

diversification of cropping sequences such as cultivating upland rice followed by bananas, cassava, or coconuts to spread risk and increase income stability. These adaptations reflect a transition from water-intensive staple crops toward more drought-tolerant and market-oriented species, prompted by prolonged dry seasons, delayed rainfall onset and increased climate variability.

Such transformations in planting patterns are consistent with climate adaptation strategies observed among smallholder farmers in other tropical regions, where erratic rainfall, extended drought periods and shifting temperature regimes necessitate adjustments in spatial and temporal cropping arrangements. Studies have shown that wider plant spacing can improve soil moisture retention, reduce pest pressure and enhance crop resilience under variable climatic conditions (44, 45). Moreover, integrating perennial and drought-resistant crops within existing farming systems diversifies livelihoods and buffers against seasonal income fluctuations, a strategy documented across Southeast Asia and sub-Saharan Africa as a key component of climate-smart agriculture (46, 47). These findings highlight the role of indigenous knowledge as both an observational tool tracking shifts in rainfall and temperature and a decision-making framework for implementing adaptive, climate-resilient cropping systems.

Farmers' adaptation strategy of climate change

Farmers in Buton Regency employ a range of adaptation strategies to cope with climate change, with adoption rates varying across sub-districts. Farmers in Kapontori exhibit high uptake of most adaptation strategies, reflecting not only their upland exposure but also the structural advantage of larger landholdings relative to South Lasalimu and Siotapina. Greater land availability broadens the feasible adaptation portfolio, enabling practices such as land-use diversification, fertiliser-based intensification and irrigation improvement patterns consistent with evidence that farm size strongly predicts climate adaptation capacity (43, 48). Thus, Kapontori's adaptive behavior appears driven less by topography alone and more by a resource-enabled ability to modify cropping systems and invest in risk-reducing measures.

The most widely implemented strategies across all areas include crop rotation and adjustments to planting calendars (100 % in Kapontori, 69 % in South Lasalimu and 68 % in Siotapina), as well as crop intensification through the use of additional fertilisers (100 % in Kapontori, 92 % in South Lasalimu and 87 % in Siotapina). These high adoption rates reflect farmers' awareness of the importance of optimising production under increasingly unpredictable climatic conditions. Furthermore, alternative land-use practices are notably prevalent in Kapontori (98 %), indicating diversification of land utilisation to mitigate the risk of crop failure.

Other strategies with relatively high adoption rates include improving irrigation facilities (93 % in Kapontori) and adopting new technologies (93 % in Kapontori and 85 % in Siotapina), underscoring the role of technology and infrastructure in strengthening agricultural resilience. Rainwater harvesting shows considerable variation in adoption, being relatively low in Kapontori (44 %) but high in South Lasalimu (80 %) and Siotapina (75 %), which may be attributed to differences in topography and access to water sources. Thank you for the constructive comment. The discussion section has been strengthened by integrating qualitative findings to explain the observed quantitative patterns, particularly the low adoption of rainwater harvesting in Kapontori. The revised text now highlights explanatory factors such as topographic conditions, water availability, existing irrigation access and local adaptation preferences, thereby providing a clearer interpretation of why adaptation differs across locations (Fig. 2).

Discussions

Farmers in Kapontori exhibited relatively lower adoption of rainwater harvesting compared to South Lasalimu and Siotapina, despite demonstrating high engagement in other adaptation practices. Qualitative findings suggest that this pattern is influenced by the interaction between upland topography, larger average landholdings and the availability of alternative water access, which collectively reduce farmers' perceived dependence on rainwater storage systems. Several respondents explained that water for

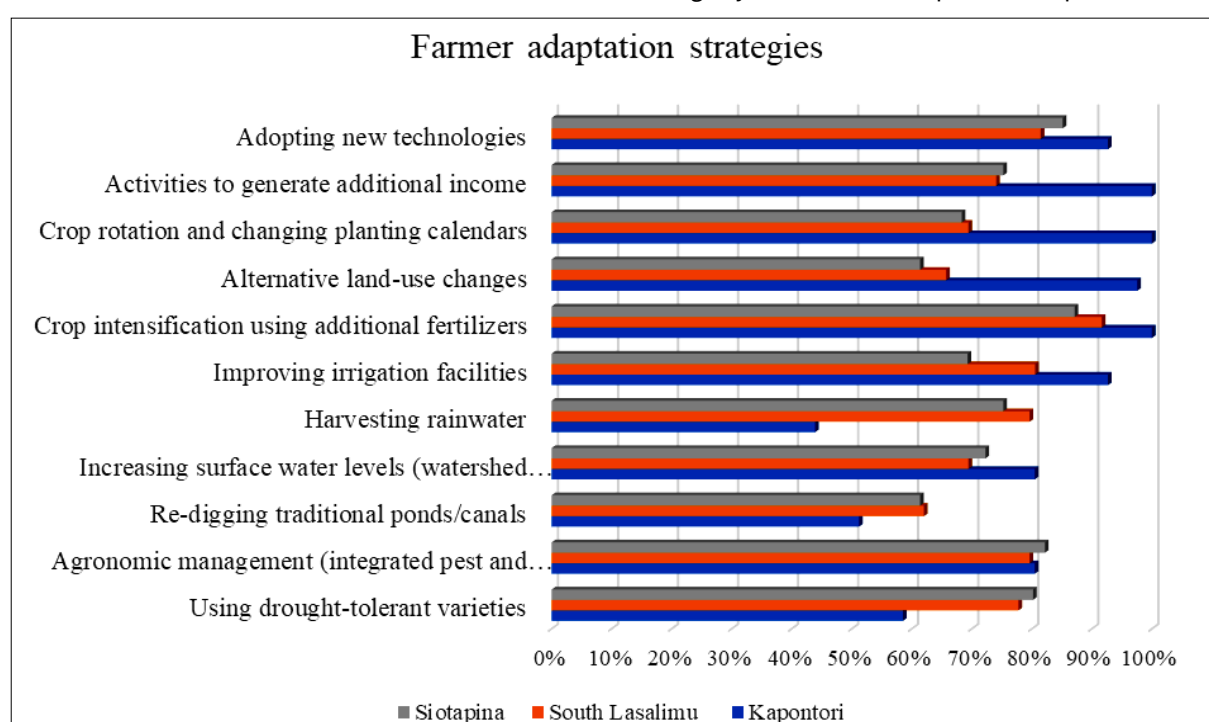


Fig. 2. Farmer adaptation strategies across the selected locations.

cultivation can still be obtained from nearby upland water flows and existing irrigation channels during parts of the growing season, making rainwater harvesting less urgent compared to areas experiencing prolonged inundation or unstable water supply. In addition, farmers in Kapontori tend to prioritise land-use diversification, crop rotation and fertiliser-based intensification as preferred adaptation strategies, reflecting locally embedded farming practices and experiential decision-making processes. These findings indicate that adaptation choices are shaped not only by climatic exposure, but also by resource availability, agroecological conditions and locally developed perceptions of risk and practicality. This pattern aligns with global literature indicating that farmers' adaptation strategies are strongly influenced by local agroecological conditions, resource accessibility and institutional capacity. Previous studies in Sub-Saharan Africa (43) and in South Asia (48) highlight that a combination of crop variety adaptation, agronomic management, land-use diversification and investments in water infrastructure constitutes an effective response to reducing production risks under climate change. The findings from Buton Regency reaffirm that multi-strategy adaptation integrating indigenous knowledge with modern technologies is crucial for enhancing the resilience of agricultural systems to climatic shocks.

The results contribute to adaptation theory by demonstrating how indigenous knowledge and local wisdom function as both an early warning system and a decision-making framework in climate-vulnerable regions. From a resilience theory perspective, the adaptive capacity of farming systems is enhanced when multiple knowledge systems traditional and scientific are integrated through local institutions. This aligns with the knowledge co-production paradigm, which emphasizes that sustainable adaptation emerges from the interaction between experiential, place-based understanding and external innovations. In the case of Buton Regency, local wisdom serves as a socio-cultural asset that lowers barriers to technology adoption, enhances trust in climate information and fosters collective action for resource management. This hybrid model of adaptation offers transferable lessons for other rural contexts facing similar climate risks.

A key contribution of this study lies in demonstrating that the co-production of knowledge is not a planned institutional process but emerges organically through everyday agricultural decision-making in diverse ecological settings. Unlike previous work that typically conceptualises co-production as the formal integration of scientific climate services with local experience, our findings show that Buton farmers engage in a bottom-up hybridisation of knowledge even where access to formal forecasts is minimal. In South Lasalimu and Siotapina, farmers reinterpret traditional weather cues through peer exchanges and selectively incorporate information from media or sporadic extension contacts, resulting in context-specific adaptations such as rainwater harvesting and modified planting calendars strategies not observed to the same extent in upland areas. This gradient indicates that co-production is shaped less by direct institutional presence and more by the interplay of social learning networks, ecological exposure and perceived environmental risk. The study thereby extends existing theoretical applications by revealing that co-production can

materialise independently of structured advisory systems and that its expression varies by agroecological zone, offering a novel empirical lens on how resilience is cultivated in under-resourced rural contexts.

Conclusion

This study demonstrates that indigenous knowledge and local wisdom were found to be central to climate change adaptation among smallholder farmers in Buton Regency. Despite the prevalence of locally developed indicators such as tree phenology, soil conditions, wind patterns, wildlife behaviour and water flow formal agricultural extension provides little to no climate-specific guidance across Kapontori, South Lasalimu and Siotapina. As a result, farmers rely primarily on experiential knowledge and community exchange to anticipate seasonal shifts, modify planting practices and manage water scarcity under increasingly variable climatic conditions. Strengthening resilience therefore requires institutional recognition of these practices and the establishment of Farmer Field Schools that formalise peer-to-peer learning while creating pathways for integrating relevant scientific information. The establishment of Farmer Field Schools (FFS) could serve as a practical mechanism for operationalising the co-production of knowledge framework in climate adaptation programs. Through participatory learning approaches, FFS can facilitate the integration of indigenous knowledge, farmer experience and scientific climate information within existing community networks, thereby strengthening locally grounded adaptation capacity. Such platforms would not only improve farmer access to climate-related information currently absent from extension services, but also enhance collective learning and peer-to-peer exchange across agroecological zones. Future research should further examine how community-based adaptation institutions influence long-term resilience outcomes and the scalability of locally embedded climate adaptation practices in other vulnerable rural regions. Together with targeted support for climate-smart technology, such community-centered approaches can foster the co-production of adaptation knowledge and enhance long-term livelihood sustainability in resource-constrained environments.

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Authors' contributions

AF conceptualised the study, designed the methodology, coordinated data collection and led manuscript writing. AF and KP carried out the data analysis, generated visual outputs and contributed to the interpretation of findings. AF, SG and KP were involved in field implementation and provided critical input during manuscript revision. AF supervised all phases of the research. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly to improve language quality. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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