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Evaluating iSAT climate-informed agro-advisories for farm decisions and system performance in Senegal's drylands

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Smallholder farmers in Africa's drylands face increasing climate risks, compounded by limited access to inputs, credit, and climate information. Climate Information Service(CIS) can support adaptation, yet adoption remains low due to insufficient localized data and limited availability of tailored advisories. This study evaluates the effectiveness of the Intelligent Agricultural Systems Advisory Tool (iSAT), a climate-informed advisory system adapted for Senegal and delivered through Interactive Voice Response (IVR) in local languages. Deployed in 18 villages, the tool reached over 2,700 farmers during the 2022 and 2023 seasons. Its impact was assessed through pre- and post-season household surveys and focus group discussions. Propensity Score Matching(PSM) was used to identify comparable treatment and control villages, and statistical analyses examined differences in yields, input and labor costs, and adoption of climate-smart practices. Farmers who received iSAT advisories recorded significantly higher yields for key crops, with millet yields increasing by 41% and groundnut yields by 21% ($p < 0.05$) compared with matched control farmers. Input and labor costs were 24% lower among advisory users, indicating improved cost-effectiveness. Cowpea exhibited no significant yield differences, reflecting its low-management requirements and the smaller number of users who cultivated it. Nevertheless, farmer feedback consistently highlighted the usefulness of the advisories for planning and managing climate risks. These findings demonstrate the potential of localized advisory systems to strengthen climate-smart agriculture in resource-limited environments. Scaling such tools will require investment in meteorological infrastructure, digital delivery platforms, and partnerships that enhance climate and digital literacy while supporting long-term adoption among vulnerable smallholders.

Keywords Climate information services, Climate change, Climate risk management, On-farm level decision making, APSIM

Climate change and increasing climate variability present critical challenges for agriculture in Africa, where dependence on rainfed farming and limited institutional capacity heighten vulnerability^{1,2}. These challenges pose significant difficulties for smallholder farmers, who produce a large share of national food supplies and support the livelihoods of most rural households. Their reliance on rainfed systems, limited financial buffers, and constrained access to inputs, extension services, credit, and climate information make them disproportionately exposed and vulnerable to climate-related shocks. Recent climate change impacts, such as declining crop productivity, livestock losses, and market disruptions due to more frequent and severe extreme weather events,

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have further intensified these vulnerabilities³. These structural constraints underscore the importance of prioritizing smallholders in climate adaptation efforts⁴.

Climate Information Services (CIS) have emerged as important tools for supporting adaptation by helping farmers plan planting dates, manage soil and water resources, and reduce climate-related risks⁵. However, several persistent barriers limit the effectiveness of CIS in West Africa. These include language constraints, sparse weather station networks, limited access to localized and high-quality data, and delivery formats that are not well suited to low-literacy users^{6,7}. Previous CIS initiatives highlight both the potential and the limitations of existing approaches. For example, Participatory Integrated Climate Services for Agriculture (PICSA) strengthened farmers' capacity for seasonal planning but offered limited support for in-season decision-making. Similarly, Senegal's CINSERE project (Climate Information Services for Increased Resilience and Productivity) enhanced climate awareness but encountered challenges related to accessibility and localized forecasting^{8,9}. These experiences point to a persistent gap in delivering CIS that are both timely and actionable throughout the farming season.

The Intelligent Agricultural System Advisory Tool (iSAT), originally developed in India, was designed to address these challenges by generating threshold-based, data-driven crop advisories tailored to farmers' needs^{10,11}. The original iSAT framework integrated historical climate data, real-time weather observations, and seasonal forecasts with crop-specific decision rules to produce actionable advisories, as detailed in Rao et al.¹¹. In its initial deployment, this integrated approach successfully supported groundnut farmers¹⁰. Although successful in its initial context, the tool relied on SMS delivery and expert-designed messages, limiting accessibility for farmers with low literacy levels or poor network connectivity. These limitations, along with lessons from earlier CIS initiatives, underscore the need for advisory systems that remain scientifically robust while being better aligned with local production realities and user capacities.

Translating these lessons to Senegal requires advisory tools that respond to local cropping systems, climate risks, and the needs of low-literacy smallholders. Despite improvements in climate service delivery across the country, smallholders in Senegal's drylands continue to lack timely, location-specific advisories that are easy to interpret and useful for both strategic (pre-season) and tactical (in-season) farm management¹². To address this gap, the iSAT framework was adopted and adjusted for Senegal through a participatory process that incorporated local knowledge, seasonal forecasts, and region-specific agronomic considerations, while presenting advisories in an accessible audio-based format suited to low-literacy users. These modifications aimed to improve relevance and usability, particularly in data-scarce environments.

This study evaluates the effectiveness of the adapted iSAT in improving smallholder farm decisions, crop systems performance including resource-use efficiencies across two growing seasons in Senegal. Specifically, the study examines: (i) farmers' exposure to and perceptions of the advisories; (ii) the influence of iSAT on key agronomic decisions; (iii) yield and economic outcomes among iSAT users and non-users; and (iv) gender-differentiated patterns in access and benefits. Addressing these questions is essential for strengthening climate-smart agriculture in dryland systems, and the findings contribute to broader efforts to develop accessible, scalable digital advisory systems for smallholder farming in West Africa.

Materials and methods

Descriptions of the study area

The study was conducted in Kaffrine, Louga, and Thies, three distinct regions of Senegal (13°48' N to 15°59' N latitude and 14°18' W to 17°9' W longitude). These regions span four agroecological zones: Niayes, Old Peanut Basin, Sylvo-pastoral, and New Peanut Zone, across four arrondissements: Barkedji, Katakél, Mabo, and Méouane. These zones differ by agro-climatic characteristics, soil type, vegetation, land use, and socio-economic factors¹³. The climate ranges from arid to semi-arid in the northeast and north to semi-humid centrally. The dry season lasts from October to June, and the rainy season from June to early October. Annual rainfall varies, with Barkedji and Méouane in Louga and Thies receiving 300–500 mm and Katakél and Mabo in Kaffrine receiving 600–700 mm. Daily mean temperatures range from 28 °C to 38 °C in Kaffrine, 26 °C to 32 °C in Louga, and 21 °C to 28 °C in Thies. The soil in the study regions, primarily loamy sandy, has low water-holding capacity and poor nutrient retention. This leads to high nutrient leaching during rainfall, necessitating frequent fertilizer applications. The soil's upper layer has low organic content (0.2 to 0.4%), indicating insufficient soil organic matter. Mixed-livestock farming systems are prevalent, with dry cereals and legumes being the primary crops grown alongside small ruminants. The practice varies with livelihood strategies and ethnic composition. As one moves from the semi-humid region (Kaffrine—the Wolof-dominated region) to the more arid regions (Louga—Fulani-dominated region), herding of cattle and small ruminants becomes more predominant (Fig. 1)¹⁴.

Development and deployment of the intelligent Agricultural System Advisory Tool (iSAT)

The study employed the Intelligent Agricultural System Advisory Tool (iSAT), a climate-informed decision-support platform designed to assist smallholder farmers across Senegal's diverse agroecological zones. iSAT provides timely guidance before and during the growing season by using rule-based decision trees whose thresholds and recommendations were informed by agronomists, extension staff, and farmers. Previous applications of iSAT have demonstrated its usefulness in supporting climate risk management in similar environments^{10,11}. The version deployed in this study (Fig. 2) integrates seasonal and short-term forecast information with expert assessments and farmers' experiential knowledge to generate localized advisories. Its development involved climate data analysis, crop modeling, decision-tree construction, advisory formulation and dissemination, and iterative refinement based on farmer feedback throughout the season.

iSAT consists of two complementary rule-based decision trees that convert climate information into actionable recommendations: a pre-season decision tree that supports strategic planning and an in-season decision tree that informs tactical management during crop growth. These decision trees were designed to

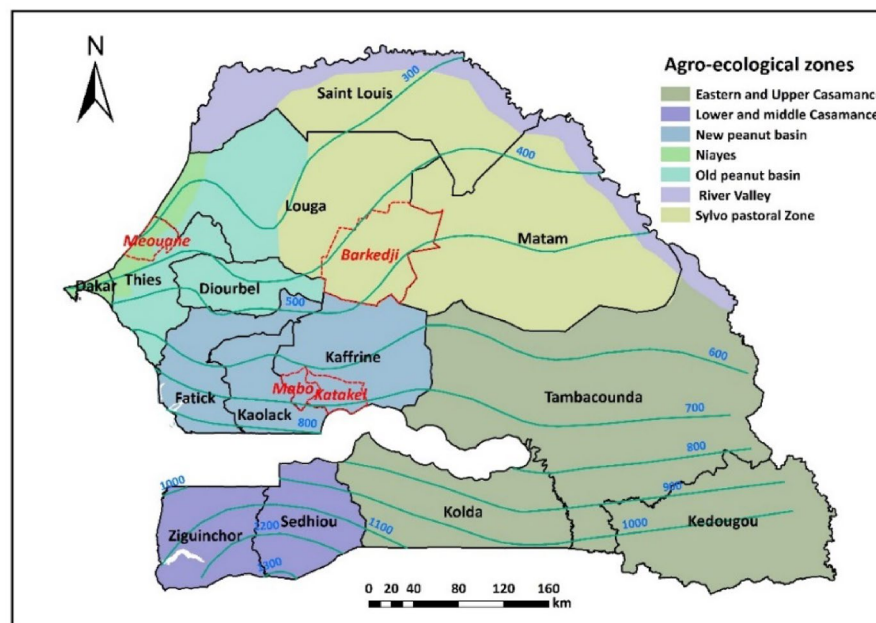


Fig. 1. The map of Senegal showing its seven agroecological zones and the distribution of the study locations over four agroecological zones: Niayes, Old Peanut Basin, Sylvo-pastoral, and New Peanut Zone. The isohyets indicate the spatial pattern of long-term annual rainfall (averaged from 1981 to 2020).

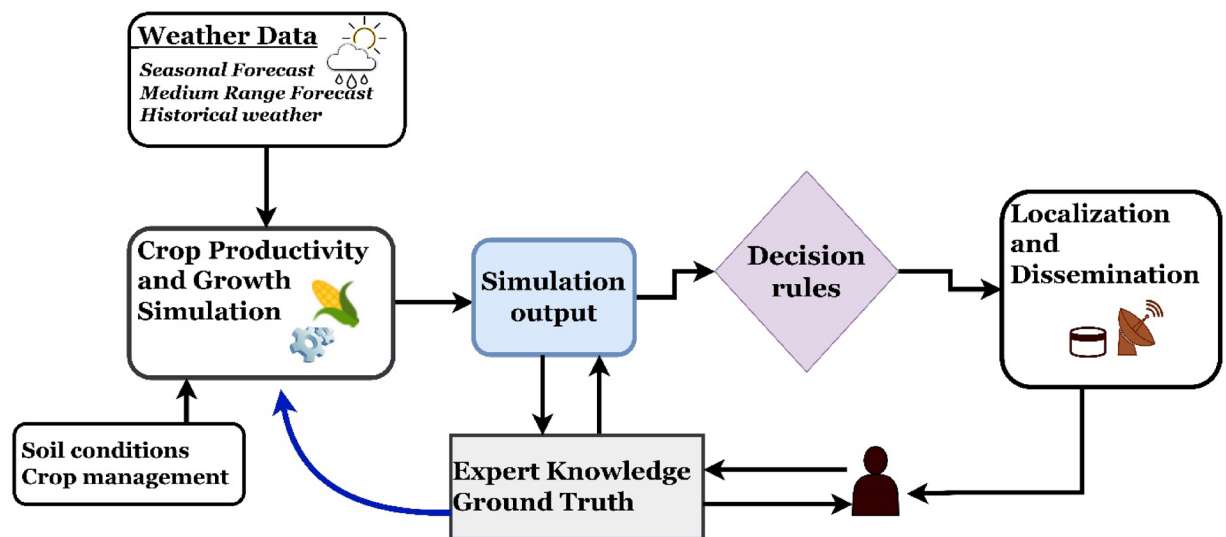


Fig. 2. The iSAT framework: A depiction of the intelligent agricultural system advisory tool's development framework.

reflect local production systems, management priorities, and common climate challenges. Their structure and methodological basis are presented in the subsections that follow.

Development of decision trees

The pre-season decision tree synthesizes two key sources of climate information: seasonal rainfall forecasts from ANACIM and Atlantic sea-surface temperature anomalies to characterize the likely conditions for the upcoming growing season. These indicators are synthesized into a limited set of seasonal outlook classifications (e.g., wetter-than-usual, wet, dry, or drier-than-usual; see Supplementary Material) based on location-specific thresholds derived from historical climate patterns and simulated crop performance. The process-based crop model APSIM (Agricultural Production Systems sIMulator¹⁵; was used to simulate crop responses under contrasting seasonal scenarios, providing an evidence base for identifying the most suitable management options. Soil parameters used in the simulations were derived from representative soil profiles of the study regions obtained from field

sampling and existing soil information for the relevant agroecological zones. These soil characteristics were incorporated into the advisory framework during system development, so farmers are not required to provide detailed soil measurements when using iSAT.

Each seasonal outlook is linked to a tailored set of agronomic recommendations that address the major pre-season decisions farmers must make, including crop and cultivar selection, planting windows, land preparation, soil and water conservation options, and the level and timing of input use. The decision rules embedded in the tree were refined using expert judgement and farmer knowledge to reflect local production constraints and feasible management strategies. The overall structure of the pre-season decision-making process is illustrated in Fig. 3, while the detailed thresholds and formal rule definitions are provided in Supplementary Material S2.

The in-season decision tree provides tactical guidance during the growing period by integrating recent weather observations with short-term forecasts and site-specific soil characteristics. The system estimates near-term soil moisture conditions using the previous week's rainfall, medium-range (two-week) forecasts, and information on the soil profile. These moisture categories (e.g., sufficient or insufficient) are determined using location-specific thresholds derived from analyses of historical rainfall–soil moisture relationships and benchmarked against CFSv2 reanalysis soil moisture estimates¹⁶. Based on these moisture assessments and the crop's growth stage, the decision tree generates recommendations related to fertilizer timing, weed management, pest and disease control, and practices to mitigate moisture stress or waterlogging. The overall logic of the in-season decision-making process is illustrated in Fig. 4, while detailed threshold derivations, data-processing steps, and the formal structure of the decision rules are provided in Supplementary Material S3.

Localization and dissemination

The messages were disseminated by a Senegalese agri-tech social enterprise, Jokalante Sarl, who translated and sent the messages generated from the iSAT platform as Interactive Voice Response (IVR) calls in the local languages of Wolof, Manding, and Pula. A total of 2,720 subscribers received these calls every Sunday during the growing seasons of 2022 and 2023, providing them with timely and relevant advisories. Subscribers, in turn, were able to provide feedback and ask questions through the IVR system. Jokalante collected their feedback and questions and immediately sent them to the iSAT production team. The team provided answers, which were then translated back into the local language and disseminated to those requesting feedback. This mechanism allowed for co-learning and co-production of more relevant and useful advisories.

Assessment usefulness of iSAT

Research design

Assessing the potential impact of the use of climate-informed agro-advisories requires both quantitative and qualitative data. Hence, the current study employed a mixed-methods research design that allows the collection of both types of data from the smallholder farmers of the study locations.

Sampling and data collection

The study employed a treatment–control village design aligned with the objectives of the Accelerating Impact of CGIAR Climate Research for Africa (AICCRA) project¹⁷. Data were collected through structured household

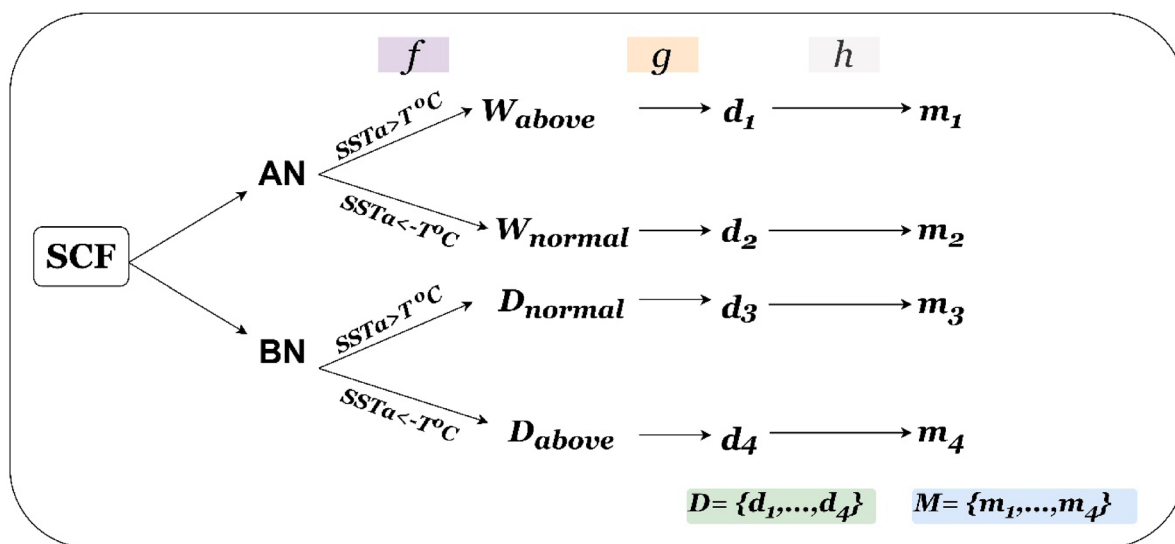


Fig. 3. Pre-season decision tree summarizing how seasonal climate forecasts (SCF) and Atlantic sea surface temperature anomalies (SSTa) are combined to classify expected seasonal conditions and derive management recommendations. Seasonal conditions include wetter than usual (W_{above}), wet (W_{normal}), dry (D_{normal}), and drier than usual (D_{above}). These conditions are translated into pre-season decisions ($d_1 - d_4$) and corresponding advisory messages ($m_1 - m_4$). Formal rule definitions are provided in Supplementary Material S2.

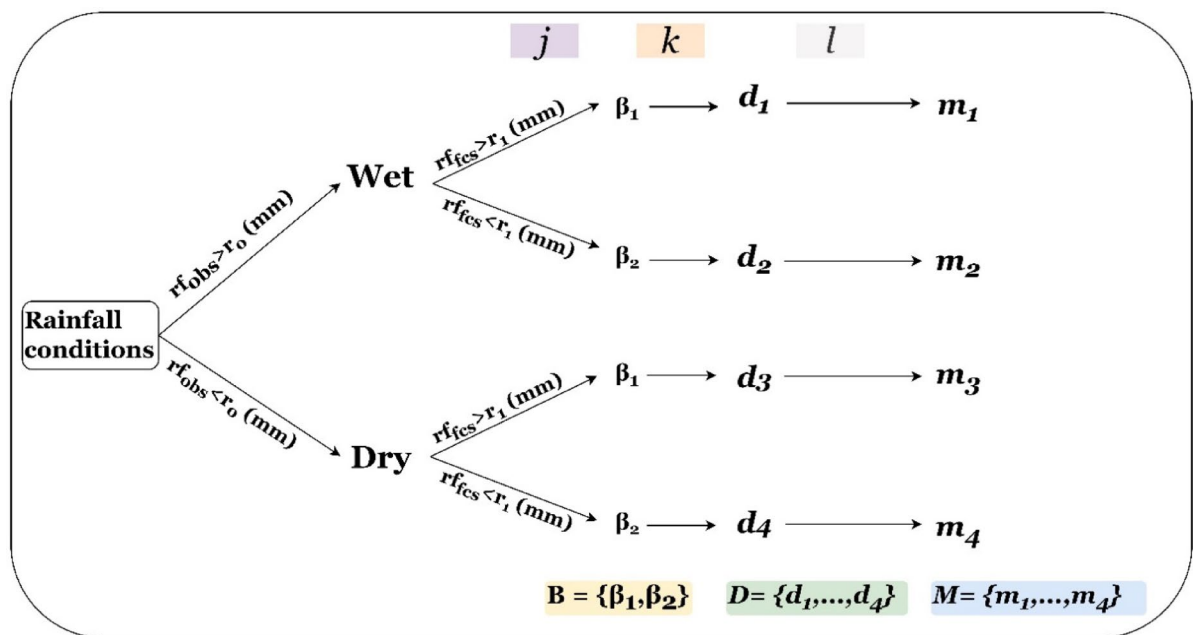


Fig. 4. In-season decision tree illustrating how recent rainfall, medium-range forecasts, and soil information are used to estimate short-term moisture conditions and guide tactical crop management. Soil moisture conditions are classified as sufficient (β_1) or insufficient (β_2) and mapped to in-season decisions ($d_1 - d_4$) and corresponding advisory messages ($m_1 - m_4$). Formal rule definitions are provided in Supplementary Material S3.

surveys and Focus Group Discussions (FGDs). Surveys captured quantitative indicators such as production metrics, input use, and Climate Information Services (CIS) adoption, while FGDs provided qualitative insights into farmers' experiences with climate information, advisory services, and agricultural decision-making. Eighteen intervention villages were selected in the regions of Kaffrine, Louga, and Thies based on their participation in project activities, established local partnerships, and alignment with the project's target agroecological zones. Comparable control villages were identified using Propensity Score Matching (PSM), following recommended practices for quasi-experimental village-level evaluations¹⁸. The geographic coordinates of all intervention and control villages are provided in Table S1, and iSAT advisories were delivered directly to registered farmers through an Interactive Voice Response (IVR) system.

Propensity scores were estimated using a logistic regression model that incorporated household demographic characteristics, crop production profiles, landholding size, livestock assets, access to agricultural extension, market distance, and agroecological features (rainfall zone, soil type, and region). Region-stratified nearest-neighbor matching was then implemented using an optimized caliper to maximize covariate comparability, combined with Mahalanobis distance within the caliper to improve local similarity between intervention and control villages. Matching was performed without replacement to ensure unique control matches for each intervention village. This approach ensured that matched controls exhibited closely aligned agroecological and socio-economic characteristics relative to intervention sites, including when drawn from adjacent regions. Covariate balance was assessed using standardized mean differences (SMDs), using commonly applied thresholds in the matching literature, where values below 0.10 indicate excellent balance and values up to 0.20–0.25 are generally considered acceptable^{19,20}. Full post-matching balance diagnostics, including SMD plots and propensity score distributions, are provided in Supplementary Material S1.

Within each matched village, households were selected using stratified random sampling based on region and predominant crops. Sampling was conducted independently for each survey round, and the surveys were cross-sectional rather than panel-based, ensuring representative samples for each treatment–control comparison. Missing data were addressed using listwise deletion, with no imputation performed. Advisory exposure was self-reported; however, to reduce recall bias and verify accuracy, enumerators asked respondents to describe the most recent iSAT advisory message they received. Despite some missing data, which was more common in control villages, the intervention-to-control ratio remained below 1.5:1 across all survey rounds, supporting robust statistical analysis.

Baseline survey

The baseline survey included 503 households: 217 from intervention villages and 286 from matched control villages across the three study clusters. Structured questionnaires captured farmers' perceptions of climate change, awareness and use of CIS, agricultural practices, and crop and livestock production. In each intervention village, FGDs with approximately 10 lead farmers explored barriers to accessing and adopting climate-informed

agro-advisories, as well as experiences, constraints, and opportunities within their farming systems¹⁷. These qualitative insights complemented the quantitative data and helped establish pre-intervention conditions.

Post-season survey

Post-season surveys were conducted at the end of the 2022 and 2023 wet seasons to evaluate farmers' exposure to iSAT advisories, adoption of climate-smart agriculture (CSA) practices, and the perceived usefulness of the advisories. Independent stratified random samples were drawn in each year using the same criteria applied at baseline. The post-season survey sampled 342 intervention and 270 control households in 2022, and 365 intervention and 262 control households in 2023. Survey modules captured advisory exposure, changes in management decisions, and uptake of CSA practices such as crop diversification and soil management. Advisory exposure was verified using the recall procedure described above. Households with incomplete responses to key variables were excluded during data quality checks. Despite these exclusions, sample ratios remained within the acceptable threshold ($<1.5:1$), ensuring balanced datasets for treatment–control comparisons. Post-season FGDs provided additional insights into farmers' experiences, perceived benefits, and constraints influencing advisory uptake.

In-depth analysis of the survey data

The data collected during the surveys underwent descriptive, inferential, and comparative analyses. Descriptive analysis summarized key variables, such as crop yields, advisory service ratings, input costs, labor expenses, and adoption of CSA practices, providing a comprehensive overview of the data from both intervention and control villages. The inferential analysis applied statistical techniques, including paired and independent t-tests, to evaluate changes in crop yields and CSA adoption rates between intervention and control villages. These tests facilitated comparisons of pre- and post-intervention outcomes, offering valuable insights into the effects of iSAT advisories. Furthermore, the Kolmogorov-Smirnov (KS) test was employed to compare the distributions of crop yields and net benefits between farmers with and without access to iSAT advisories. This non-parametric test assessed significant differences, particularly in the yield distributions of millet and groundnuts.

The study compared data from control and intervention villages to measure the impact of the climate-informed agro-advisories. Alongside the analyses, a simple cost-benefit analysis was conducted. This analysis considered yield and costs associated with input, labor, and advisories. The 'cost of advisories' refers to the financial expenditure a farmer incurs when paying the service provider, Jokalante, for weekly voice messages throughout the season. The main goal of this analysis was to quantify the economic benefits of using these advisories in the designated study area. The net benefit for the grown crops was calculated as follows:

$$\text{Net benefit } (CFAha^{-1}) = \text{Total benefit} - \text{Total cost}$$

Whereby:

$$\text{Total benefit} = \text{Crop yield } (kgha^{-1}) \times \text{Crop price } (CFAkg^{-1})$$

$$\text{Total cost} = \text{Cost of input} + \text{Cost of labor} + \text{Cost of advisories}$$

$$\text{Cost of advisories (CFA)} = \begin{cases} 0 & \text{control village} \\ 2000 & \text{intervention village} \end{cases}$$

The crop prices for 2022 and 2023 were obtained from the Selina Wamucii platform²¹. This comparative analysis provided valuable insights into the usefulness and effectiveness of the advisories in improving agricultural practices in the face of climate variability and change.

Methodological and data limitations

Some methodological constraints may have influenced advisory precision. The climate inputs used in iSAT combined ENACT satellite datasets⁸, station observations, and soil moisture estimates from NCEP's CFSv2 reanalysis¹⁶, all of which carry uncertainties related to spatial resolution and local representativeness. To reduce the impact of these uncertainties, thresholds and recommendations were reviewed by agronomists and extension agents and continually refined through the farmer feedback loop during each season. Advisory exposure was self-reported and subject to recall bias, though enumerators verified responses by asking farmers to recount their most recent message. Occasional network disruptions also affected IVR delivery. Nonetheless, mobile phone access was high¹⁷, and messages were translated into local languages, limiting barriers to understanding.

Ethical declarations

All methods in this study were carried out in accordance with relevant institutional guidelines of the participating partners in the AICCRA project and national research regulations. Ethical considerations were addressed through adherence to institutional protocols of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), and the study received ethics approval under IEC Clearance Number: IECICRISAT/30,082,022/06¹⁷. Informed consent was obtained from all participants prior to their involvement in the study.

Results

Deploying climate-informed agro-advisories

Barriers to the adoption of climate-informed agro-advisories

Several challenges were identified that hinder the adoption of climate-informed agro-advisory services in the study area. The first challenge was the climate illiteracy of most farmers, which significantly affected their ability to comprehend and utilize the received climate information (most respondents had no formal schooling or had attended Franco-Arabic schools; see Supplementary Table S7). The probabilistic nature of the forecasts was not well understood, and the language used didn't guide them toward actionable decisions. The second challenge was the absence of sufficient location-specific (high-resolution) agroclimatic information, crucial for farmers to make informed decisions throughout the growing period. Farmers reported a lack of advice on key agricultural practices such as selecting the right (season-specific) crop varieties, managing pests and diseases, and storing harvests. The third challenge was the poor alignment of the received climate information with the cropping calendar, referring to the mismatch between the timing of the weather forecasts and the agricultural calendar followed by the farmers. For instance, a delayed warning of heavy rains issued after a farmer has already applied fertilizer can lead to nutrient leaching, resulting in financial loss. In response to these challenges and findings, the climate-informed agro-advisory tool was designed and tailored to enhance the utilization of CIS and the adoption of agro-advisories.

Deployment of the intelligent Agricultural System Advisory Tool (iSAT)

During the 2022 and 2023 seasons, iSAT was deployed in 18 villages to deliver weekly Interactive Voice Response (IVR) advisories in Wolof, Manding, and Pula. Messages provided localized guidance on seasonal outlooks, land preparation, and crop-specific management for millet, maize, groundnut, and cowpea. Over the two seasons, 2,720 farmers engaged with the advisories, 23% of whom were women. To illustrate the format and content of these advisories, one representative pre-season example is included below, while an example of an in-season advisory is provided in the Supplementary Material.

Part 1: General advisory.

Good rain is expected. The season has the potential to grow short- to medium-duration maize, sorghum, millet, peanut, and cowpeas in the 15 June to 31 July planting window when you receive at least 30 mm of rain. Improved varieties are highly recommended to increase crop performance and yields. The upcoming weekly advisories will include further information about weather forecasts and excellent agronomic practices for the forthcoming season in your area.

Part 2: Land preparation.

After good rains, at least 30 mm per week, and before sowing, harrow the soil well for fine plowing.

Crop varieties.

Millet: Souna-3, SL28, Thialack-2 and SL423; *Groundnut*: Fleur 11,78–936, Taaru, Komkom, Tosset, Rawgadu, Rafeet kaar; *Maize*: Opatampa, Mais Jaune LG336, EVDT 97 D8, Jaune de Bambey, Early Thai; *Cowpea*: Thieye, Leona, Melakh, Yacine.

Benefits and impacts of iSAT in the study area

Survey data analysis from this study reveals that the iSAT tool's deployment positively impacted the beneficiaries. The tool's usefulness and its significant effects on farmers with access to iSAT, compared to those without, are detailed below:

Resource optimization

The study conducted a comparative analysis of the cost of input and labor per hectare during the growing season for farmers with and without iSAT advisories. The findings of this study indicate that farmers who received iSAT advisories incurred an average cost of 363,774 CFA (~US\$600) ha⁻¹ for labor and inputs, including seeds and fertilizer. This is 24% lower than the 479,898 CFA (~US\$790) ha⁻¹ cost for those without iSAT advisories ($p < 0.001$ t-test).

Increased yield and profitability

The impact of iSAT advisories on crop yields was evaluated among farmers in the intervention and control villages. The use of iSAT advisories significantly improved the yields of millet and groundnuts (p -value < 0.05). The farmers who received iSAT advisories experienced a remarkable increase in both millet and groundnut yields, with a notable 41% and 21% improvement, respectively, when compared to control farms. For cowpea, mean yields in both intervention and control villages were below 0.5 t ha⁻¹ and close to the typical yield reported for the area (~0.45 t ha⁻¹), with no statistically significant difference between farmers who had access to iSAT advisories and those who did not ($p = 0.94$; Fig. 5).

An in-depth analysis was conducted of yield distributions for both the treatment group (with iSAT agro-advisories) and the control group (without iSAT agro-advisories) to determine if significant differences existed between the two groups. Using the Kolmogorov-Smirnov (KS) test, statistically significant differences were observed in the yield distributions of millet and groundnuts (p -value < 0.000), indicating that iSAT agro-advisories had a measurable impact on these crops. However, the KS test showed no significant differences in cowpea yield distributions between the groups. These findings are visually represented in Figure S5 of the supplementary material, which illustrates the yield distribution differences for millet, groundnuts, and cowpeas.

iSAT advisories led to significant improvements in net benefits (measured in CFA ha⁻¹) across all crops, including millet, cowpeas, and groundnuts, compared to control villages. In millet cultivation, there was a notable shift from a negative gross margin of approximately 45,000 CFA ha⁻¹ in villages without iSAT advisories to a positive net return of 250,000 CFA in villages with iSAT advisories during the 2022 and 2023 seasons.

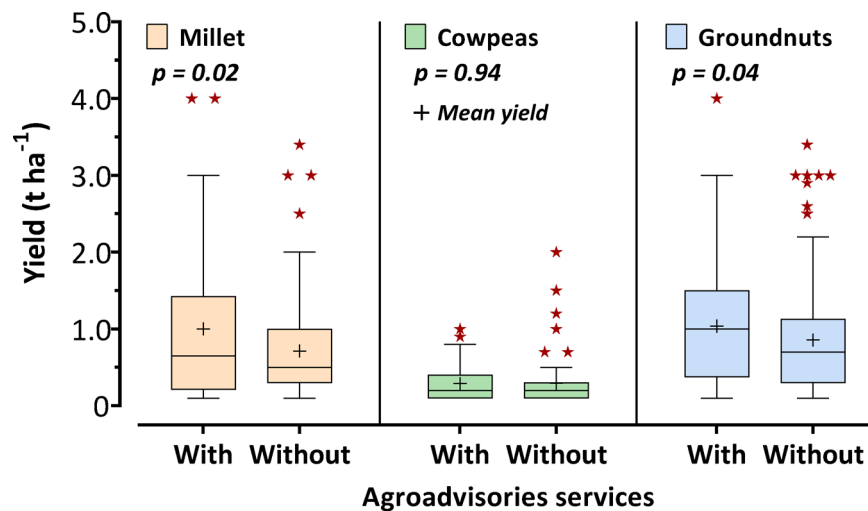


Fig. 5. Comparative distribution of crop yields for farmers with and without access to iSAT. The graph illustrates the differences in crop yield between two groups of farmers: those who used iSAT (labeled as 'With') and those who did not (labeled as 'Without'). The p-values provided denote the statistical significance of the observed differences. The red stars are outliers.

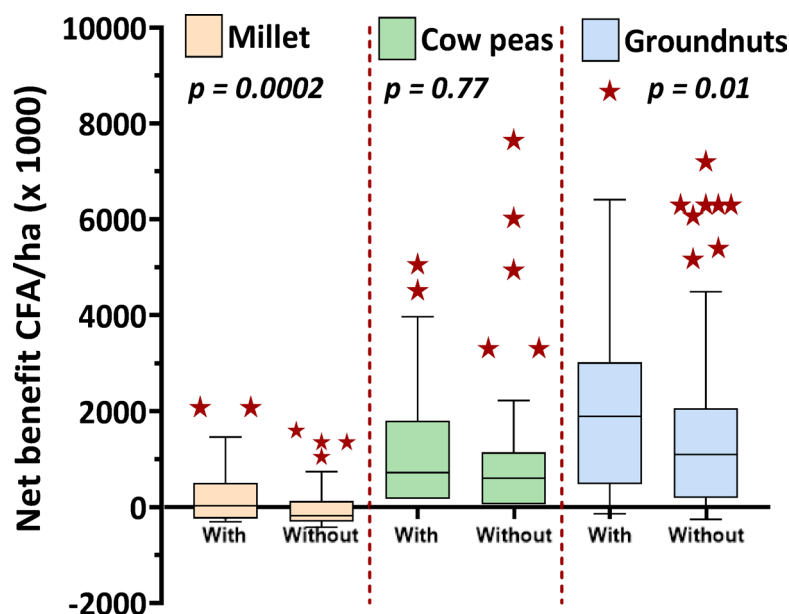


Fig. 6. The graph illustrates the differences in net benefit achieved between two groups of farmers: those who used iSAT (labeled as 'With') and those who did not (labeled as 'Without') in the 2022 and 2023 cropping seasons.

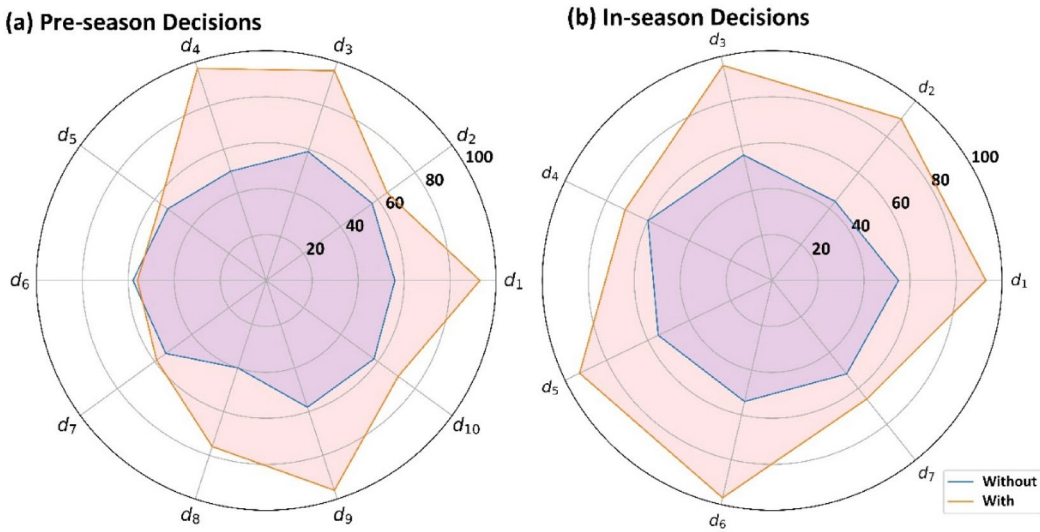
This signifies a substantial improvement in the economic viability of millet farming under iSAT guidance. Similarly, cowpea and groundnut cultivation in villages with iSAT advisories also resulted in higher net benefits. Specifically, cowpeas saw an 8% increase in net benefit, likely attributed to lower production costs, while groundnuts experienced a 36% increase compared to villages without iSAT advisories (Fig. 6). The distributions of the net benefit are visualized in Figure S6 of the supplementary material. Millet and groundnut showed statistically significant differences between the "With iSAT" and "Without iSAT" groups (p-value < 0.000), while cowpeas showed no significant difference between the groups.

Decision support

Farmers in both the control and intervention villages were evaluated based on their implementation of a set of decisions before and during the season, as outlined in Table 1. The objective was to identify any variations in decision-making processes and the level of confidence shown by farmers in both the control and intervention

Nature of decision		
Decision	Pre-season	In-season
d ₁	Crop and planting decisions: Crop selection, crop diversification, planting strategies e.g., intercropping, rotation, etc.	Crop management decisions: Applying fertilizers to address nutrient deficiencies, weed control, and pesticide application
d ₂	Resource allocation decisions: land allocation for different crops, allocation of labor, budget for seeds, fertilizers, and other input	Environmental and climate-related decisions: Implementing protective measures for crop application, taking actions to mitigate heat stress
d ₃	Soil preparation and fertilization decisions: land preparation techniques; application of organic matter, compost, or cover crops; type and quantity of fertilizers	Harvest and post-harvest decisions: Deciding on the optimal timing for crop harvest, monitoring crop maturity, choosing appropriate storage
d ₄	Climate and weather considerations: Anticipate potential weather risks based on weather information, deciding on planting dates that align with your local climate patterns	Resource management decisions: Adjusting labor allocation, managing labor shortages, prioritizing equipment use based on urgency and efficiency
d ₅	Pest and disease management decisions: pre-season pest management plan, deciding on the selection and timing of pesticide applications, identifying potential disease-prone crops plan and intervention	Risk management decisions: Regularly inspecting crops for pests and disease symptoms to make timely decisions, deciding on further intervention
d ₆	Financial and budgeting decisions: Creating a budget for the upcoming season, allocating funds for purchasing new equipment, allocation of fund	Continuous monitoring and observations: Regularly observing crop health, making decisions on resource allocation based on yield expectations
d ₇	Marketing and sales decisions: Identifying target markets, deciding on packaging and labeling, and allocating resources for transportation and distribution	Overall strategy and adaptation: Adapting strategies in response to evolving conditions, making continuous improvements
d ₈	Risk management decisions: Anticipating potential risks, e.g., extreme events, creating contingency plans for unexpected challenges, deciding on insurance options	
d ₉	Long-term sustainability decisions: Planning for sustainable practices, allocating resources for conservation efforts, deciding on the integration of agroecological principles	
d ₁₀	Operational and timing decisions: Decide on the timing of various pre-season operations, allocating time for monitoring and early detection of pest and disease issues	

Table 1. Definition of the pre-season and in-season decisions made by the farmers in the 2022 and 2023 seasons.



The numbers represent the % of respondents (Households) and the N = 353

Fig. 7. Pre-season (a) and in-season (b) decisions {d₁,...,d_n} made by farmers, with (represented in orange) and without (represented in blue) iSAT agro-advisories in the study region. The value ‘N’ represents the average number of respondents for the years 2022 and 2023.

villages when making these decisions. Farmers in the intervention villages demonstrated greater proactivity in executing timely pre-season planning and implementing good agronomic practices to mitigate climate risks throughout the season, in contrast to those in the control villages (Fig. 7). These practices include decisions on crop selection, resource allocation, soil preparation, climate considerations, pest management, financial planning, and in-season management. In-season management involves tactical decisions related to crop management, harvest timing, resource management, risk management, and continuous monitoring, as detailed in Table 1. Furthermore, long-term sustainability practices (d₉) were crucial. These included planning investments each season in conservation practices such as soil erosion

prevention and water conservation (e.g., watershed terraces). These decisions ensure that farming practices remain viable and environmentally sustainable over time.

Statistical analysis revealed significant differences in the implementation of both pre-season and in-season management practices between the intervention and control villages, with p -values of 0.004 and 0.001, respectively. Farmers who received the iSAT agro-advisories came from diverse socio-economic backgrounds. As illustrated in Fig. 7, the decisions made by farmers were influenced differently by iSAT among farmers. For instance, the number of farmers who made their crop planning decisions (d_1) differed from those who allocated their resources based on iSAT advisories (d_2). This variation highlights the influence of socio-economic factors, e.g., input purchasing power, on how farmers utilized and benefited from iSAT agro-advisories.

Given the diverse agroecological zones (Fig. 1), the influence of iSAT advisories on decision-making likely varied across the intervention clusters. To better understand this, an in-depth assessment was conducted to examine how farmers within these clusters aligned their pre- and in-season activities with the iSAT advisories and the extent to which they relied on these advisories for decision-making. The study's findings revealed a statistically significant difference in pre-season decision-making influenced by iSAT advisories among the three intervention clusters (p -value = 0.04). However, no significant difference was observed for in-season decision-making (p -value = 0.583). A Tukey test revealed significant differences in the influence of iSAT advisories on pre-season decision-making between the Daga Birame and Méouane clusters (p -value = 0.03). Specifically, farmers in the Méouane cluster were more likely to base their decisions on the iSAT advisories, with an average of 97% influenced by the advisories, compared to 92% in the Daga Birame cluster. However, no statistically significant differences were observed in the influence of iSAT advisories on pre-season decision-making between the Daga Birame and Thiel clusters (p -value = 0.514) or between the Méouane and Thiel clusters (p -value = 0.256). Detailed statistical data can be found in the supplementary materials in Tables S3, S4, and S5.

Improved seasonal planning and crop management

The effectiveness of agro-advisories in supporting farmers with their seasonal planning and crop management activities was assessed. Figure S7 in the supplementary illustrates feedback from respondents across different clusters regarding the application of iSAT advisories in crop planning and management. The analysis indicated that the advisories were timely and accurate, offering valuable guidance for various planning aspects. On average, at least 70% of respondents regarded the advisories as reliable. These farmers reported that the advisories enhanced their decision-making confidence, facilitated timely decisions, and aided in selecting appropriate crops, all essential for effective crop planning and management throughout the season. In the study area, crop planning involves selecting suitable crops for the season and determining inputs such as fertilizers and pesticides. Additionally, effective crop management encompasses the timely application of pesticides, fertilization, weed control, and water management. These aspects were comprehensively addressed in the advisories, which were provided weekly to farmers during the 2022 and 2023 cropping seasons. This consistent communication assisted farmers in making informed decisions, thereby enhancing crop planning and management effectiveness.

Climate risk management

The study found that iSAT advisories significantly reduced climate risks within the intervention area. These advisories, offering weather forecasts and tailored recommendations based on anticipated weather and soil conditions, provided farmers with the knowledge to anticipate challenges like waterlogging and pest infestations. Respondents across all three clusters confirmed this, with at least 80% stating that the advisories enabled timely decision-making (see Figure S6 in the supplementary). For instance, during the first and second weeks of August, a period known for high pest infestations, farmers received alerts and guidance on addressing these infestations effectively. This critical information helped mitigate pest risks, ensuring crop success. These positive impacts are further highlighted in the results depicted in Figure S8.

Farmers' perceptions regarding the challenges they faced in terms of the difficulty level of various activities and achieving better crop yields were assessed. The aim was to understand the relative ease or difficulty, as well as the effectiveness, of farmers in intervention villages in managing climate risks compared to those in control villages. Figure S8 provides a comparison of the challenges or difficulty levels, ranging from very easy to very difficult, encountered by farmers in managing climate risks, with a focus on the differences between two groups: those with access to iSAT advisories and those without. The study's findings revealed that farmers without access to iSAT advisories encountered significantly greater difficulty in responding to and managing risks by performing the mentioned operations than those utilizing iSAT advisories throughout the season. Particularly concerning tactical management activities during the season, farmers without iSAT found it more challenging to manage climate risks than those using iSAT advisories.

Increased adoption of climate-smart agriculture practices

The study further examined the drivers of climate-smart agriculture (CSA) adoption using a logistic regression model (Table S5). The results show that iSAT advisory use is a statistically significant predictor of CSA adoption (p = 0.000), indicating that farmers who engaged with the advisories were more likely to adopt at least one CSA practice. Descriptive statistics from the survey also show that among the 261 households participating in the AICCRA project, 79% of those who adopted CSA reported using iSAT advisories. Together, these findings suggest that iSAT contributes to CSA uptake by providing timely and relevant agronomic information that supports farmers' decisions to adopt improved practices.

Gender-disaggregated characteristics and advisory use

Gender-disaggregated descriptive statistics for intervention households are provided in Supplementary Table S6. Women farmers using iSAT advisories cultivated smaller areas than men (5.5 ha vs. 6.6 ha) and were less

likely to grow millet, groundnut, or maize, but more likely to grow cowpea and other secondary crops. Although they represented only 23% of advisory recipients, women reported similar involvement in farm management decisions: over 90% said they chose crops, planned sustainable practices, and managed fertilizer and pest control. Advisories influenced both men and women, especially crop selection (95% of women, 96% of men), though fewer women felt supported in resource allocation (87% vs. 92%). Actual cost reductions were also similar (46% for women, 52% for men), showing that women benefited even with less access.

Discussion

Barriers to the adoption of climate-informed agro-advisories

Several structural and informational barriers continue to shape the adoption and effective use of climate-informed agro-advisories in the study area. Consistent with findings from other West African contexts^{22,23}, farmers highlighted gaps in climate literacy and difficulties interpreting probabilistic information, which limit their ability to act on advisories and to provide feedback that could strengthen service delivery. Challenges related to the limited spatial precision of available climatic data also emerged, reinforcing earlier evidence that data scarcity and coarse-resolution products constrain the development of truly location-specific advisory services in the Sahel²⁴.

Gender-based constraints were another important barrier. Although women constituted only about one-quarter of iSAT users, their participation patterns reflected long-standing structural inequalities in access to land, inputs, and decision-making authority³². Similar to observations across Senegal²⁵ and other SSA countries²⁶, these constraints reduced women's ability to act on advisory recommendations even when the information was relevant. The findings therefore support the broader claim that improving the reach and effectiveness of CIS requires addressing underlying resource disparities, not only enhancing information delivery.

These challenges align with continent-wide analyses showing that climate service uptake is often hindered by weak institutional coordination, limited investment in meteorological infrastructure, and insufficient involvement of local communities in the design of advisory services⁵. The barriers observed in this study thus reflect both local production realities and broader systemic issues in CIS delivery across Africa, underscoring the need for advisory systems that integrate high-quality data with inclusive, user-responsive approaches.

Breaking through barriers with iSAT

The implementation of iSAT helped address several persistent challenges in climate service delivery by integrating multiple data sources with local knowledge and expert interpretation. The system's use of ENACT satellite products⁸, station observations, and soil moisture estimates from CFSv2¹⁶ enabled the generation of location-appropriate thresholds for decision-making in a data-scarce environment. While such hybrid approaches have been recommended for improving advisory relevance in the Sahel²⁷, few systems have operationalized them at scale. The present study demonstrates that combining observational data with agronomic expertise and farmer experience can mitigate the limitations of coarse-resolution climate information and improve the contextual fit of advisories.

The approach strengthened climate literacy and trust in advisory information through structured engagement with lead farmers and extension agents. Evidence from other participatory climate services, such as PICA^{26,28}, indicates that co-learning processes enhance farmers' understanding and confidence in climate information. The experiences reported here align with these findings, suggesting that structured interpretation support and continuous feedback mechanisms are critical for bridging the gap between climate information and practical decision-making. Importantly, these interactions ensured that advisories remained consistent with local cropping calendars and evolving field conditions, thereby addressing a common limitation in climate service delivery highlighted by Ouédraogo et al.²³. These findings underscore the contribution of participatory mechanisms in enhancing the credibility and contextual relevance of climate services.

Beyond improving understanding, the iSAT design promoted more meaningful engagement between farmers, extension agents, and advisory providers by combining pre-season interpretation sessions, continuous IVR feedback channels, and rapid responses to farmer queries. This reflects broader evidence that advisory systems are most effective when they integrate technical information with local production contexts and when users perceive advisories as credible and actionable^{12,29}. The findings from this study imply that embedding climate information within iterative, user-responsive frameworks contributes to overcoming the limitations of one-way dissemination. By demonstrating that hybrid data systems, participatory engagement, and structured feedback loops collectively improve the suitability and uptake of climate-informed advisories, the iSAT experience offers a significant contribution to ongoing debates on how climate services can be designed to function effectively in dryland smallholder systems.

Benefits and limitations of iSAT

Benefits of iSAT

The study demonstrated the significant impact of iSAT advisories in the Kaffrine, Louga, and Thies regions of Senegal across four agroecological zones. iSAT enhanced farmers' ability to navigate climate variability by providing timely and locally attuned guidance across multiple stages of production. This pattern mirrors broader findings from dryland West Africa showing that advisory systems grounded in localized information can strengthen decision-making and improve production outcomes¹²⁸. Notably, the stronger responsiveness seen in the more climate-vulnerable cluster i.e., Méouane, suggests that advisory tools may deliver the greatest value where exposure to climate risk is highest, highlighting the differentiated demand for climate information across agroecological gradients.

iSAT also contributed to more proactive planning by helping farmers interpret expected seasonal conditions and adjust key production decisions accordingly. This improvement in anticipatory behavior is consistent

with evidence that decision-support tools can strengthen farmers' adaptive capacity by reducing uncertainty around crop choice and timing²⁹. The role of facilitated interpretation, echoing processes used in participatory approaches such as PICSA^{26,28}, appears especially important here and reinforces the idea that advisory systems are most effective when information is both locally relevant and easily actionable. These behavioral gains were reflected in the stronger yield responses observed for millet and groundnut among advisory users, although the degree of benefit varied across crops.

While most staple crops showed clear improvements in yield among iSAT users, cowpea presented a different pattern. For cowpea, yield differences between farmers with and without iSAT advisories were not statistically significant, although the boxplots suggest a tendency toward higher yields among advisory users. This reflects the crop's management context in the study area: cowpea is commonly intercropped and requires relatively few in-season interventions beyond early fertilizer application and weeding³¹, limiting the influence of advisory messages on its performance. Cowpea was also grown more frequently by women, who constitute only about 23% of advisory recipients and generally have more constrained access to land and inputs. The smaller number of cowpea-growing advisory users, combined with these constraints, may have reduced the statistical power to detect an effect. These factors help explain the absence of a significant difference, even though the direction of the yield response aligns with other crops.

Beyond yield benefits, the study found that farmers using iSAT advisories achieved notable reductions in input and labor costs by adopting more targeted fertilizer and pest management strategies. These efficiencies translated into higher net benefits and supported improved food security and livelihoods, complementing broader findings that climate-informed advisories can enhance farm profitability and resource-use efficiency³⁰. Environmental co-benefits such as improved soil fertility management and reduced risks of nutrient loss were also reported, underscoring iSAT's contribution to climate-smart agricultural practices.

Gender patterns observed in the study point to structural factors that shape how men and women can act on advisory information. Although women represented a smaller proportion of advisory users, their engagement across key management decisions suggests that the advisory content was relevant when access was achieved. At the same time, differences in landholding, crop portfolios, and access to inputs indicate that women face additional constraints that may limit their ability to fully benefit from advisories. These findings reinforce the need for climate information services to integrate more gender-responsive design features, addressing both access barriers and the resource disparities that influence the practical application of advisory messages²⁶.

Limitations and prospects

While iSAT improved farmers' decision-making, several limitations remain. The advisories assessed in this study focused mainly on cropping systems; livestock guidance was introduced only in the final project year, leaving insufficient data to evaluate its usefulness. The tool also lacked real-time market information because consistent price data were unavailable in the study regions, limiting farmers' ability to link production decisions with market opportunities. Gender disparities in access to land and inputs also influenced who could benefit from the advisories. Since women formed a smaller share of users and typically have fewer resources, the gains observed may not yet be fully equitable. Strengthening the inclusiveness of advisory services will be important for future scaling. Finally, the evaluation covers only two seasons. Although short-term improvements were clear, longer-term studies are needed to understand how continued use of iSAT affects farming practices, environmental outcomes, and livelihoods over time.

The long-term sustainability and scaling of iSAT will depend on reliable delivery channels, continued accessibility for farmers, and strong institutional support. The tool's simple rule-based structure and use of freely available climate datasets make it technically scalable, especially if future versions can be delivered not only through IVR but also through modern digital channels such as SMS, mobile apps, and chatbots. Socio-economic factors, including equitable access for women and resource-constrained households and the affordability of advisory services, will influence how widely the tool can be used. Institutional partnerships with meteorological agencies, extension services, and local organizations remain essential for keeping the advisories accurate, updating thresholds, and embedding iSAT within existing agricultural support systems. Strengthening these elements will help ensure that iSAT remains useful and sustainable as it expands to new regions and production systems.

Conclusion

This study demonstrates that climate-informed agro-advisories delivered through iSAT can improve farmers' decision-making and support more climate-resilient production in Senegal's rainfed systems. Across two seasons, farmers who accessed iSAT advisories reported clearer guidance on crop planning, more efficient use of inputs and labor, and, for several major crops, higher yields than non-users. Crop-specific responses, particularly the limited effect observed for cowpea, highlight the need to consider management practices and gendered resource constraints when assessing advisory impacts.

The findings also show that simple rule-based decision trees, supported by reliable climate data and regular feedback from extension agents and farmers, can generate locally relevant advisories even in data-scarce environments. While this evaluation focused primarily on cropping systems, future work is needed to assess newer components such as livestock advisories and to examine longer-term behavioral and livelihood impacts. Ensuring equitable access, especially for women and resource-constrained households, remains essential for maximizing the benefits of digital advisory services.

The sustainability and scalability of iSAT will depend on strengthening delivery channels, including complementary digital platforms, and on building institutional partnerships that support continuous updating of thresholds and advisory content. Investments in climate information infrastructure, extension capacity, and

inclusive digital access will be critical for embedding tools like iSAT within broader climate-smart agriculture strategies.

Scaling climate-informed advisory tools such as iSAT will require strengthening national climate information systems, enhancing the digital and climate literacy of farmers and extension agents, and expanding delivery channels through IVR, SMS, mobile applications, and chatbots. Ensuring that women and resource-constrained households can access and act upon advisories is essential for equitable benefits. Continued investment in meteorological data infrastructure, local institutional partnerships, and adaptive feedback mechanisms will further improve the reliability, reach, and usefulness of advisory services.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Received: 17 June 2025; Accepted: 10 March 2026

Published online: 26 March 2026

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Acknowledgements

This research was funded by the Academy for International Agricultural Research (ACINAR). ACINAR, commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ), is being carried out by ATSAF e.V. on behalf of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Also, we acknowledge support from the Tropical Plant Production and Agricultural Systems Modelling (TROP-AGS) division of the Department of Crop Sciences, University of Göttingen, Germany, the International Livestock Research Institute (ILRI), and the World Bank-funded AICCRA project (Accelerating Impacts of CGIAR Climate Research for Africa)—Project ID 173398—is acknowledged for funding the authors Jacob Emanuel Joseph and Anthony M Whitbread in this study.

Author contributions

J.E.J., A.M.W., and R.P.R. conceptualized the study and designed the methodology. J.E.J. conducted formal analysis, curated data, and prepared visualizations. F.M.A. and R.D. validated findings, provided resources, and curated data. O.N.W. and A.F. supervised the research and contributed resources. N.A.K. and B.S. supervised the dissemination of agro-advisory services and provided ICT support. O.K. contributed resources. J.E.J. wrote the original draft, and A.M.W., R.P.R., F.M.A., and J.E.J. reviewed and edited the manuscript. All authors reviewed and approved the final version.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-026-44231-y>.

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