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Review article

Linking weather and climate information services (WCIS) to Climate-Smart Agriculture (CSA) practices

Tafadzwanashe Mabhaudhi [a,c,*], Tinashe Lindel Dirwai [b,c,*], Cuthbert Taguta [c,d], Aidan Senzanje [d], Wuletawu Abera [e], Ajit Govid [f], Elliott Ronald Dossou-Yovo [g], Ermias Aynekulu [h], Vimbayi Grace Petrova Chimonyo [c,i]

[a] Centre on Climate Change and Planetary Health, London School of Health and Tropical Medicine, Keppel St, London WC1E 7HT, United Kingdom
[b] International Water Management Institute, 12.5 km Peg, Mazowe Rd, Harare, Zimbabwe
[c] Centre for Transformative Agriculture and Food Systems, University of KwaZulu-Natal, Scottsville, Pietermaritzburg, South Africa
[d] Bioresources Engineering, University of KwaZulu-Natal, Scottsville, Pietermaritzburg, South Africa
[e] International Centre for Tropical Agriculture (CIAT), Accra, Ghana
[f] International Centre for Agriculture Research in Dry Areas (ICARDA), Cairo 11728, Egypt
[g] Africa Rice Center (AfricaRice), Bouake, Côte d'Ivoire
[h] World Agroforestry (ICRAF), Nairobi, Kenya
[i] International Maize and Wheat Improvement Centre (CIMMYT), 12.5 km Peg, Mazowe Rd, Harare, Zimbabwe

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ABSTRACT

Objective(s): This study synthesises existing knowledge on the linkages between Weather and Climate Information Services (WCIS) and Climate-Smart Agriculture (CSA) practices. Specifically, it addresses the following questions: (1) What is the current status of knowledge on WCIS and CSA in the global south, specifically the African continent?, (2) Are WCIS effectively tailored and linked to CSA practices and technologies to improve agricultural water management (AWM) amongst smallholder farmers?, and (3) How can linking WCIS and CSA facilitate the identification, appraisal and prioritization of regionally differentiated and context-specific climate-appropriate technologies and policies that enhance agricultural water management at various levels (field, farm, scheme, and catchment)?
Methods: The study used the Preferred Reporting Items for Systematic and Meta-Analysis Protocol (PRISMA-P) guidelines. It involved the search of the Scopus and Web of Science databases for peer-reviewed articles, books, and grey literature focussed on the global south.
Results: The results revealed that seasonal forecasts were the main WCIS available to farmers who utilised them to plan predominantly for irrigation and water harvesting activities. Daily forecasts were linked to practices such as irrigation. The study also revealed that temperature and rainfall (amount and distribution) were predominantly disseminated to farmers through extension services. The dominant CSA practices used by farmers were carbon-smart (e.g., composting), water-smart practices (improved varieties, irrigation, RWH), weather-smart practices (IPM & crop insurance), and nitrogen-smart practices (organic fertiliser, crop diversification). Advisories on carbon-smart practices generally aligned closely with the start and end of rainfall information, while the water-smart practices were corroborated with the rainfall onset, end of rainfall season, and rainfall intensity. Weather smart practices were strongly linked to drought, temperature, and rainfall distribution, whereas nitrogen smart practices were linked with the end of rainfall and temperature.
Conclusions: The study concluded that distinct linkages exist between WCIS and various CSA categories. The study argues that increasing access to WCIS can facilitate the adoption and scaling of CSA practices.

Significance.
Integrating WCIS with CSA enables practitioners to create tailored and regionally differentiated interventions for building resilient agri-food systems across scales. Our study highlights how WCIS can

* Corresponding authors.
E-mail addresses: Tafadzwanashe.Mabhaudhi@lshtm.ac.uk (T. Mabhaudhi), t.dirwai@cgiar.org (T.L. Dirwai).

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enhance the selection of appropriate CSA practices for different farming systems and spatial scales. We provide a simple framework for guiding farmers, decision-makers, policymakers, and practitioners in integrating WCIS into the deployment and scaling of CSA.

Introduction

The efficacy and execution of on-farm crop and water management practices to reduce water loss and enhance water use efficiency strongly rely on weather and climate information. Weather and Climate Information Services (WCIS) refer to the systems and processes that provide data, forecasts, advisories, and warnings about weather conditions and climate patterns to various users, including farmers, policymakers, and the public. These services typically include short-term weather forecasts, seasonal climate predictions, real-time weather data, and historical climate information. The purpose of WCIS is to support decision-making. It is used extensively in sectors like agriculture, water management, and disaster risk reduction, and it offers timely and accurate information that can help users prepare for and respond to weather- and climate-related challenges.

Weather and Climate Information Services (WCIS)[1] are increasingly seen as foundational for building resilience and enabling adaptation to the impacts of climate change in agriculture and other climate-sensitive sectors. Global expenditure totalling USD 56 billion was channelled towards these services between 2011 and 2015 (World Meteorological Organization, 2015). Georgeson et al. (2017) showed that although this investment represents progress in WCIS use, disparities in WCIS access exist, especially between the global North and South. In the global south, especially sub-Sahara Africa (SSA), investments in total WCIS (less than 2 billion USD) and per capita WCIS (approximately $1.50) are significantly lower than the global average of about $12.50 per capita (ACPC, 2021). The lower investments in WCIS in SSA likely contribute to the information gap on its usefulness. This leads to subpar alignment with global standards and frequent discrepancies with risk reduction practices and climate adaptation practices.

Given that weather and climate variability and change will continue to act as an agricultural risk multiplier, institutes like the United Nations Framework Convention on Climate Change (UNFCCC) through funding bodies like the Green Climate Fund and Weather and Climate Information Services for Africa (WISER) are working to bridge the gap and ensure the provision of relevant WCIS. However, there is an emerging need to provide quality WCIS tailored to end users' needs and matched to farmers' practices. According to Hermansen et al. (2021), end-users have pre-established decision-making processes and tools for their purposes. This means that WCIS must be adapted to what end-users already have in place (Born et al., 2021). Within SSA, farming landscapes are heterogeneous, and the WCIS needed varies accordingly. For example, Coulibaly et al. (2015a) revealed that seasonal rainfall outlook, the onset of rains, extreme weather events, and the number of days of rainfall were the most needed WCIS by pastoralists in Malawi. In contrast, the agro-pastoralists in Tanzania identified expected rainfall over the season and probability of extreme events as the most preferred WCIS (Coulibaly et al., 2015b). In Ghana, Antwi-Agyei et al. (2021) reported that seasonal, monthly, and daily weather forecasts, as well as the occurrence of heavy rainfall, were the most preferred WCIS by farmers.

Understanding that there are differences in farmers' perceptions of climate information and usability, the National Oceanic and Atmospheric Administration's (NOAA) Regional Integrated Sciences and Assessments (RISA) programs have developed a suite of Useful to Usable tools that include subscription, tools and applications for the U.S. Corn Belt (Haigh et al. 2018). The majority of SSA lacks these Useful to Usable tools, and there is a growing criticism that WCIS specialists focus more on the accuracy of the observations and forecasts with minimal effort toward improving the usability and fit-for-purpose aspects (Lemos et al., 2012; Soares et al., 2018). The usability, relevance, and scale issues further solidify the need to avoid blanketed/one-size-fits-all investment approaches when generating weather and climate information and subsequent packaging and dissemination. Hence, it is important to provide WCIS relevant to the local context and fit-for-purpose across heterogeneous farming systems. The context-specificity and scalability of WCIS means they must meet the information needs and facilitate the scale-up of adaptable practices among smallholder farmers.

Sub-Saharan African farming communities are predominantly rural and rely on agriculture for food production and driving economies. Therefore, adopting climate-smart agriculture (CSA) practices is a critical intervention to avert food and nutrition insecurity and poverty in the context of climate change (Azadi et al., 2021). In this context, linking CSA and WCIS is critical for de-risking food production systems in the region, particularly in semi-arid regions where environmental challenges such as low and erratic rainfall, poor soil quality, and frequent droughts are major production challenges. In Kenya, Ngigi and Muage (2022) postulated that access to WCIS and advisory services positively affected farmers' decisions to adopt CSA. Using WCIS significantly increased the adoption of water management and multiple cropping practices by 6.8 % and 5.6 % in Ghana (Djido et al., 2021). Partey et al. (2018) highlighted how the availability of WCIS facilitated the effective implementation of local CSA practices, particularly half-moon or *zai pits,* for rainwater harvesting in selected regions in West Africa. McKune et al. (2018) evaluated the linkages between WCIS and the uptake of CSA practices in Senegal and Kenya and revealed that farmers who received WCIS changed their farming practices. Born et al. (2021) explain that access to climate services supports the use of CSA by improving farmers' willingness to have access and use CSA to mitigate climate-related stresses. Linking WCIS and CSA could allow farmers to improve operational and strategic decision-making for increased resilience and adaptation across scales (Vincent et al., 2018). Furthermore, exploring the dissemination channels provides insights into effectively providing disaggregated WCI across the gender divide for decision-making (Ngigi and Muange, 2022). Despite this recognition, the above literature has not explicitly established usability and fit-for-purpose aspects of the disseminated WCIS for CSA practices.

This study reviewed and synthesized the knowledge of the linkage between WCIS and CSA practices, particularly in agricultural water management. It specifically developed a simplistic and generic framework for optimizing agricultural water use, given the large importance of rainfed systems and the relevance of water in such systems in SSA. Specifically, the study addresses the following questions:

I. Are WCIS effectively tailored and linked to CSA practices and technologies for improved management amongst smallholder farmers?
II. Can WCIS drive the adoption of CSA? In which context and at what scale(s)?
III. Can linking WCIS and CSA facilitate the identification, appraisal and prioritization of regionally differentiated (field, farm, scheme and catchment) and context-specific climate-appropriate technologies and policies that enhance agricultural water management?

Methods

The study followed the revised step-wise Preferred Reporting Items

[1] Weather and climate information services (WCIS) can be defined as "activities that deal with the generation and provision of climate information to a range of users to support climate-resilient development and inform climate-related decision-making and climate-smart policy and planning. They involve the acquisition, processing, packaging and delivery of weather and climate variables such as temperature, rainfall, wind, soil moisture, ocean conditions and extreme weather indicators'' (UNECA, 2021).

for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Page et al. (2021). The PRISMA protocol is a robust approach for performing evidence-based systematic and scoping literature reviews. For ease of understanding, we formulated a study pathway to guide the readers that include i) assessing the current status of WCIS, ii) evaluating whether WCIS are tailored to and connected with CSA, iii) identifying barriers to linking WCIS and CSA, iv) reviewing WCIS as potential drivers for CSA across different scales, and v) linking WCIS to CSA for context-specific, climate-appropriate technologies and policies (Fig. 1).

Definition of terms

CSA is a synergistic approach combining multiple interventions to improve natural resources and agricultural water management (Thottadi and Singh, 2024). Initially, the definition of CSA was only limited to agricultural practices (Kaptymer et al. 2019) cited by Li et al. (2024)). However, the subject matter has since evolved to touch on social-economic-political, socio-ecological, socio-demographic, and socio-economic factors (Nyasimi et al., 2017; Lawson et al., 2020; Li et al., 2024). Therefore, in this study, we broadly defined CSA as practices that expand beyond in-situ agricultural production to different direct and indirect value chain activities dictated by the socio-economic, socio-ecological, socio-political, and socio-demographic settings. This study adopted a categorised approach to climate-smart agriculture (CSA) practices by Mthethwa et al. (2022) that encompass six categories, namely, carbon, energy, knowledge, nitrogen, water and weather smart (Table 1). Table A1 (See Appendix 1) also includes the weather and climate information terms and the associated decision-making categories for WCI operationalisation.

Literature handling

The review was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Page et al., 2021). The PRISMA protocol standardises literature search, screening and synthesis. The study searched the Scopus database and the Web of Science (WoS) platform. In the WoS platform, the search was conducted utilising the WoS core collection using the following list:

(ALL (climate smart agriculture) AND TITLE-ABS-KEY (conservation agriculture* **OR** plant* pits **OR** zai pit* **OR** rain water harvest* **OR** half-moon* **OR** half?moon pond* **OR** Basin* **OR** contour **OR** contour bunds* **OR** terrac* OR mulch* **OR** cover crop* **OR** agro-forestry* **OR** intercrop* **OR** rotation **OR** strip?crop* **OR** crop divers* **OR** irrigat* **OR** drip irrigation* **OR** micro?irrigation* **OR** solar powered irrigation* **OR** sub?surface irrigation* **OR** (tolerant AND (variet* OR cultivar*)))) **AND** (TITLE-ABS-KEY (climate information **OR** climate infor* service* **OR** weather service* **OR** weather forecast* **OR** climate advi* **OR** season* forecast)). Grey literature was searched in Google Scholar and government websites. Duplicate check, text extraction and study figures were done in R Software (v4.1.2; R Core Team 2023).

Eligibility and inclusion–exclusion criteria

The inclusion–exclusion criteria applied are defined in Table 2 (see Appendix). Article screening was done based on title, abstract, and keywords. Predatory journals were filtered and excluded according to Beall's list of predatory journals (Beall, 2011).

Bias reporting

Two independent reviewers formed the authorship team and conducted the screening process. The screening was done by scoring an article's relevance against a five-point Likert scale (1 – least irrelevant

Fig. 1. Study pathway.

Table 1
Definition and practical examples of the different CSA categories applied in this study.

Category	Definitions/Examples	References
Carbon	Crop rotations, intercropping, agroforestry, and minimum tillage	Umar, 2021; Tadesse and Ahmed, 2023; Baffour-Ata *et al.*, 2024
Energy	Solar energy for irrigation and residue composting to improve soil organic matter	(Umar, 2021; Tadesse and Ahmed, 2023)
Knowledge	Farmer-to-farmer knowledge exchange and belonging to a local or farmer organization	(Chandra *et al.*, 2017; Amoak *et al.*, 2023)
Nitrogen	Minimum tillage, intercropping with legumes, composting, site-specific fertilizer recommendations	(Saito et al., 2015; Ouédraogo *et al.*, 2019; Mujeyi *et al.*, 2022; Tadesse and Ahmed, 2023; Tilahun *et al.*, 2023)
Water	Planting cover crops, rainwater harvesting, deficit irrigation, drought-tolerant varieties, early planting, adjusting planting dates, land and water development in inland valleys	(Magesa *et al.*, 2023; Tadesse and Ahmed, 2023; Dossou-Yovo et al., 2022)
Weather	Mobile phones to disseminate climate information, indigenous knowledge systems to predict weather patterns and events, internet, television and newspapers to access climate information, index-based insurance	(Chandra *et al.*, 2017; Ncoyini *et al.*, 2022; Baffour-Ata *et al.*, 2024)

Table 2
Inclusion-Exclusion criteria applied in the study.

Inclusion	Exclusion
Articles published in English	Articles from predatory journals as outlined in the updated Beall (2020) list of predatory journals.
Original research in peer-reviewed journals	Articles not published in English
Conference proceedings	Full articles that could not be retrieved
MSc and PhD theses Government gazettes	Articles with insufficient and irrelevant results, discussion and conclusions
Books and book chapters	

and 5 – denoting most relevant). The scoring criteria were also aided by Koutsos et al. (2019) criteria for ranking article relevance. In situations with conflicting scoring, discussions were held between the two reviewers until a consensus was reached. A third independent reviewer acted as an arbiter if necessary (Page et al., 2021b).

Bibliometrics analysis

The search outcomes from Scopus and WoS were input into Biblioshiny, an R package for bibliometrix analysis by Aria and Cuccurullo (2017). The Biblioshiny app provides a web interface for bibliometrix, and it was used to map the extent of knowledge generation in WCIS and the subsequent utility in the global North and South hemispheres.

WCIS and CSA framework development

To develop a guiding framework for designing bespoke interventions across scales, the study considered the following factors:

Spatial scale: the food production systems and management practices vary across scales in Africa; hence, addressing the scale of operation is essential in providing a weather and climate bundle that matches the CSA practice. We adopted the scales described by Uhlenbrook et al. (2022),

Typology: Farming typologies vary, as outlined by AU (2020), and are determined by ecological factors, production systems, input use, and production objectives (Sakané et al., 2013; Dossou-Yovo et al., 2017), which vary across scales and, thus, require fit-for-purpose interventions to match the scale of operation. The typology here relates not to scale but to the context, such as target farmers' adaptive capacity and socio-economic status. In this study, farmer typologies were defined by the African Union Irrigation Development and Agricultural Water Management (AU-IDAWM) framework (see AU, 2020 for methodology),

Governance: This factor was disaggregated to present institutional, gender and social inclusion (GESI) issues. The idea was to interrogate cultural compatibilities and local and traditional institutions as well as inclusiveness involved in food production practices and systems, such as water and nutrient management and market access, to mention a few.

Results and discussion

Literature search

The search strategy yielded 106 articles. After duplicate checking, 84 articles remained. The screening process yielded 80 articles that were used for qualitative synthesis. The PRISMA flow chart (Fig. 2) summarizes the described process.

Status of WCIS in Africa: Bibliometric mapping

The conceptual structure map (Fig. 3) had two clusters, i.e. red (n = 35 words) and blue (n = 16 words). The red cluster dimension showed relations between agriculture and key climate variables such as rainfall and the application of numerical models. This could signify those studies where climate science and data analytics applications were used to predict the impacts of future seasonal variations on agricultural performance. Use case examples include studies by Magesa et al. (2023) applied linear regression models to analyse near-future and far-future climate data on agricultural outcomes in Africa, whilst Sharma and Dubey (2023) applied regression models to predict rainfall conditions and the subsequent yields achieved from the prediction. Forecast data, if available, can be essential for planning planting dates and selecting the right variety to suit the rainfall conditions, thus cutting the yield gap. Prediction data requires statistical downscaling for localisation and making the data contextual (Ncoyini et al., 2022).

The blue cluster showed elements of indigenous knowledge as one of the general keywords in the cluster. Indigenous knowledge forms part of traditional climate adaptation strategies (Mkuhlani *et al.*, 2020; Amoak *et al.*, 2023; Balasha *et al.*, 2023). Soil conservation (which was close to indigenous knowledge) entails improved soil organic matter, subsequently improving water-holding capacity and land stewardship to protect agricultural lands from degradation. The proximity can be interpreted as follows: soil conservation can be combined with indigenous knowledge systems for adaptive management for enhanced resilience (Makate *et al.*, 2016; Ouédraogo *et al.*, 2019).

It was observed in the literature that despite a wider application of numerical weather prediction models to fill the gaps in weather data, minimal access to WCIS exists amongst smallholder farming communities in Africa. Challenges range from limited earth observation (remote sensing) data processing capacity, a lower number of weather stations across the continent and the fact that the limited quality of data obtained from the existing weather stations, etc, greatly limits access to WCIS (Chiputwa *et al.*, 2020; Baffour-Ata *et al.*, 2024).

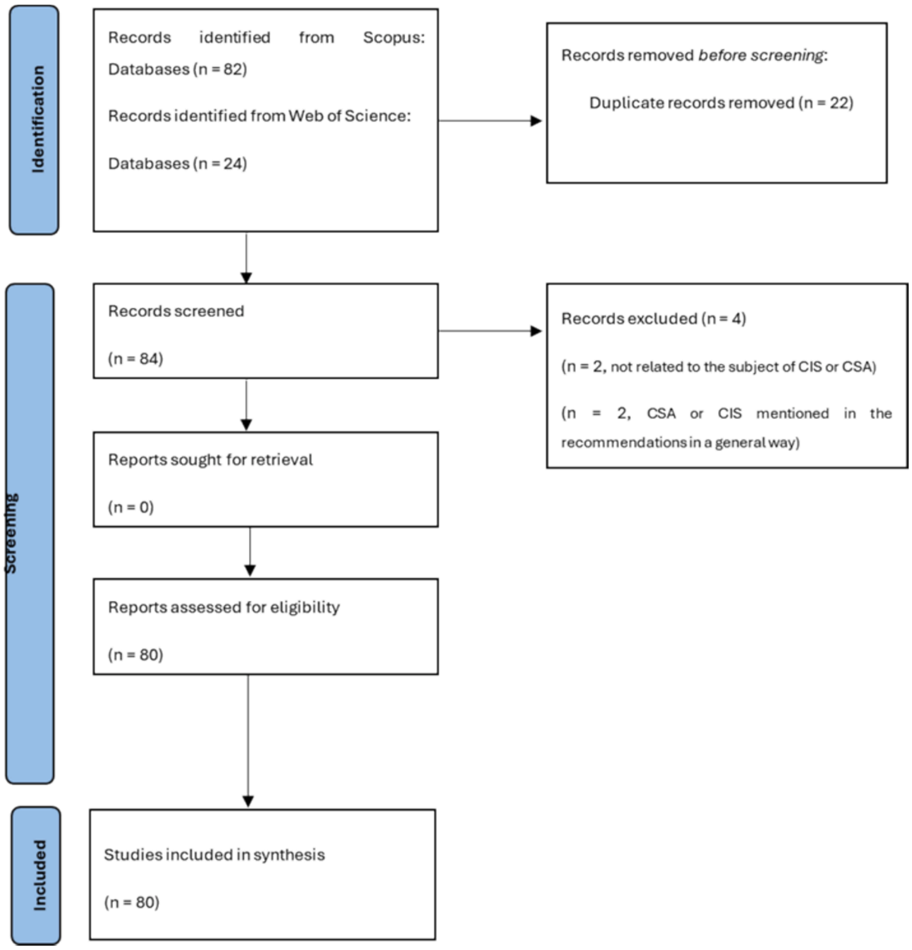

Fig. 2. PRISMA flow chart showing the number of articles: (a) retrieved from the WoS and Scopus search platform and database, respectively, (b) screened and included in the qualitative synthesis.

Linkages between WCIS and CSA practices

An in-depth content analysis from the included articles was performed to map the different forecast information to the CSA practices. The Sankey diagram (Fig. 4) illustrates the connections between different types of weather forecasts (seasonal, monthly, and daily) and various climate-smart agriculture (CSA) practices.

Based on our understanding, the interpretation of Fig. 4 is as follows: Seasonal forecasts are the most referenced and connected to a wide range of CSA practices (Fig. 4), such as crop diversification, mulching, improved varieties, agroforestry, conservation agriculture, and irrigation. We regard these practices as high-impact practices, requiring strategic and tactical planning and focusing on long-term decisions that shape agricultural spaces' overall direction and function (Freitag et al., 2024). Weather information such as seasonal rainfall amount, rainfall onset and cessation, seasonal drought occurrence and seasonal temperature are important for these strategic and tactical planning events. The mentioned practices necessitate long-range (three to four months) weather predictions to optimize their effectiveness and sustainability, enabling better-informed decisions and preparedness. For instance, the role of climatic trends in planning crop/tree combinations (intercropping and relay cropping) and sequencing (rotations, intercropping, hedgerows) is essential as these practices support slow-moving processes such as soil carbon build-up (Pisante et al., 2015) or tree establishment and growth (Love et al., 2009). In agroforestry, species selection is a major challenge in drought-prone areas to ensure maximum productivity and prevent tree mortality.

Access to climate information facilitates proactive measures by farmers, such as selecting suitable rice varieties for predicted seasonal climates. Sisay et al. (2023) demonstrated that farmers with access to climate information could mainstream agroforestry and conservation agriculture approaches and increase crop diversification more effectively than those without such access. This improved use of approaches was attributed to reliable information on current and future temperature and rainfall, allowing farmers to choose improved varieties (early maturing, drought-resistant, and disease/pest-resistant) and technologies. Seasonal forecasts are also critical for irrigation water budgeting and reservoir management. They provide long-term weather predictions that aid in planning water allocation, storage, and usage strategies. Accurate seasonal forecasts enable efficient water resource management, ensuring crops receive adequate moisture throughout critical growth stages, enhancing agricultural productivity and sustainability.

To some extent, monthly forecasts were linked to practices such as crop insurance and minimum tillage (Fig. 4). These practices can be classified as moderate-impact as they align with operational planning, involving medium-range (two weeks to one month) adjustments and routine activities and associated to this is Monthly temperature and rainfall distribution and intensity. Practices such as adopting improved crop varieties and crop insurance benefit from periodic weather updates to optimize efficiency and manage risks effectively. For example, a water requirement satisfaction index (WRSI) in Malawi was developed as a micro-insurance for groundnut farmers. This index used a weighted sum of cumulative rainfall during the 130-day growing period, with individual weights assigned to dekadal (10-day) rainfall totals (Meze-Hausken et al., 2009). In Germany, adapting weather index insurance to capture critical plant growth phases allowed farmers to anticipate and

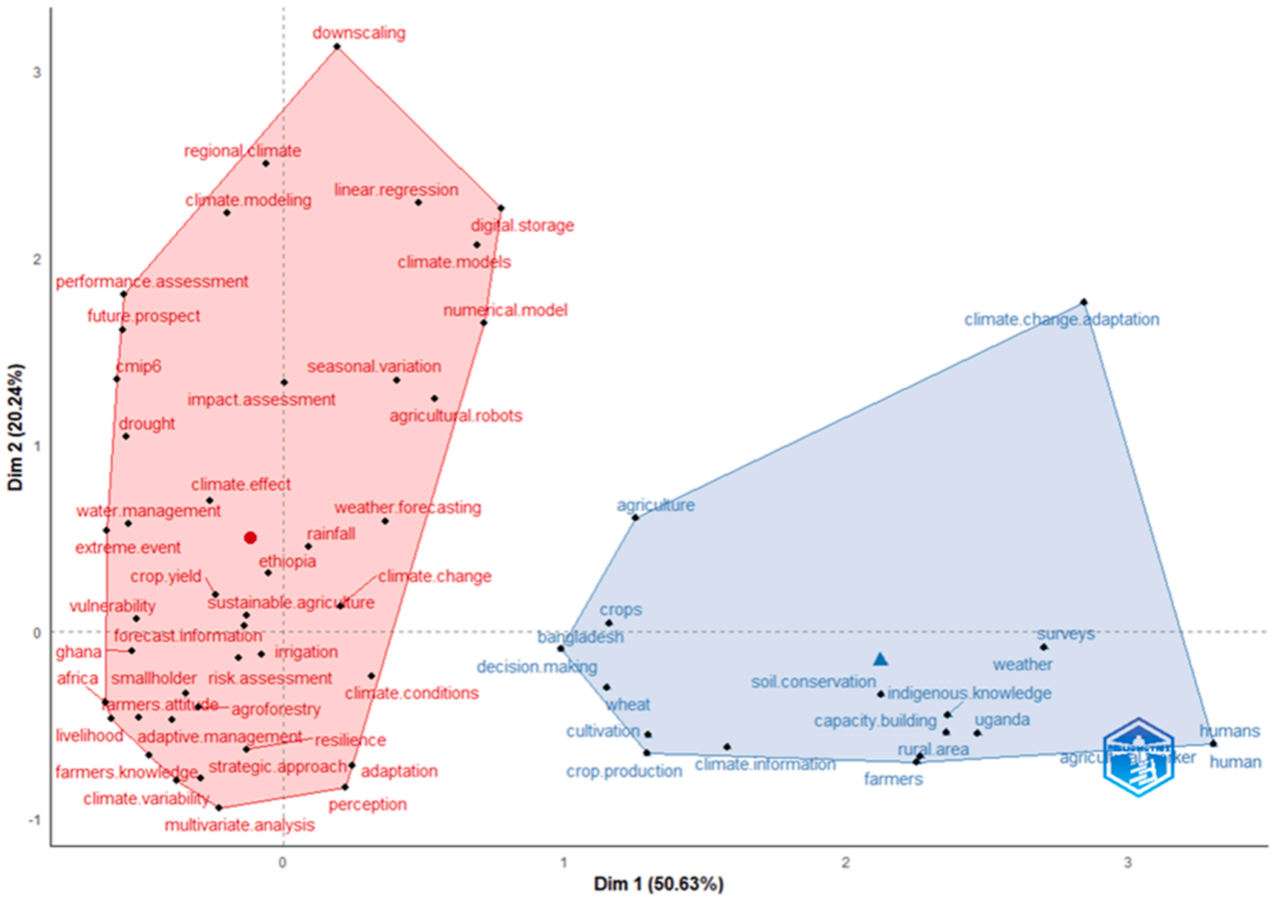

Fig. 3. The dominant clusters of studies generated from the factorial analysis. The red cluster of studies (n = 35 words) spanned across the vertical (0,-1) and, (0,0) and (0,3) quadrants with a word variance of 20.24 %. The red cluster showed a better word association between WCIS-related research and agricultural outcomes than the blue cluster, which showed a word variance of 50.63 %. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cope with drought risks in winter wheat (Dalhaus et al., 2018). In Senegal, forecasts provided before the season enabled farmers to identify suitable cropping patterns, fertilizers, and improved varieties for adaptation (Ouedraogo et al., 2018). Similarly, in India, access to information on weather and climate-related forecasts (such as droughts, windstorms, and extreme temperatures) positively influenced planting dates and fertilizer management (Khan et al., 2021).

Though less frequently mentioned, daily forecasts are crucial for immediate decision-making practices. Immediate-impact practices are crucial for tactical planning, necessitating quick, short-range (daily – 10-day) responses to immediate conditions. Practices like drip irrigation and integrated pest management depend on real-time weather information to promptly make rapid decisions and address current issues. Daily forecasts are essential for drip irrigation management, providing precise and timely data on evaporative demand. Informations such as daily rainfall and temperature fluctuations, humidity and wind speed and direction are important for rapid decisions. This allows farmers to accurately adjust water delivery, ensuring crops receive the optimal daily moisture. Guo et al. (2021) concluded that daily drip irrigation based on daily forecasts increased wheat yield and water use efficiency. Timely information regarding the developmental stages of pests can facilitate early detection and control, increasing efficiency and effectiveness (Crimmins et al., 2020). Bebber (2022) indicated that humidity is important for predicting fungal disease outbreaks in crops. Weather-based pest forecasting is crucial for the efficient use of pesticides, the overall protection of valuable crops, crop productivity, and economic returns for the farmer (Bebber, 2022; Crimmins et al., 2020).

Dissemination channels of WCIS and the respective weather & climate information bundles in Africa

Fig. 5(a) visualizes the dissemination of various climate information services (CIS) types through different channels, highlighting the predominant role of extension services and radio. Extension services are the main conduit for most CIS, including critical information on rainfall and drought. Our field experience from Egypt, Morocco and India reveals that e-extension systems can play a great role in rapidly disseminating bespoke/contextual climate information and climate services. It is more effective when bundled with other services. This is especially critical in countries with weak conventional extension systems in the global south. Digitally aided extension services (e-extension) can play a great role. However, this necessitates that we develop the digital infrastructure that is conducive to this. This includes the phone-based applications co-designed in local languages, understanding the stakeholder's needs, and having adequate subject matter specialists to manage and update the CSA contents. These e-extension solutions must be scaled with the right capacity development and outreach activities and patronized by the government with the right enabling environments (finance, policies and partnerships) (ICARDA, 2024). According to Mkwambsi et al. (2020), who emphasized the need for a strong government-led extension service framework that will support and coordinate the delivery of advisory services, it will allow the inclusion of tasks that can strengthen farmer preparedness in case of any seasonal risks. The distribution of drought information through extension services further emphasises their strategic importance in providing timely and actionable insights for mitigation and preparedness. Rainfall data, such as onset and

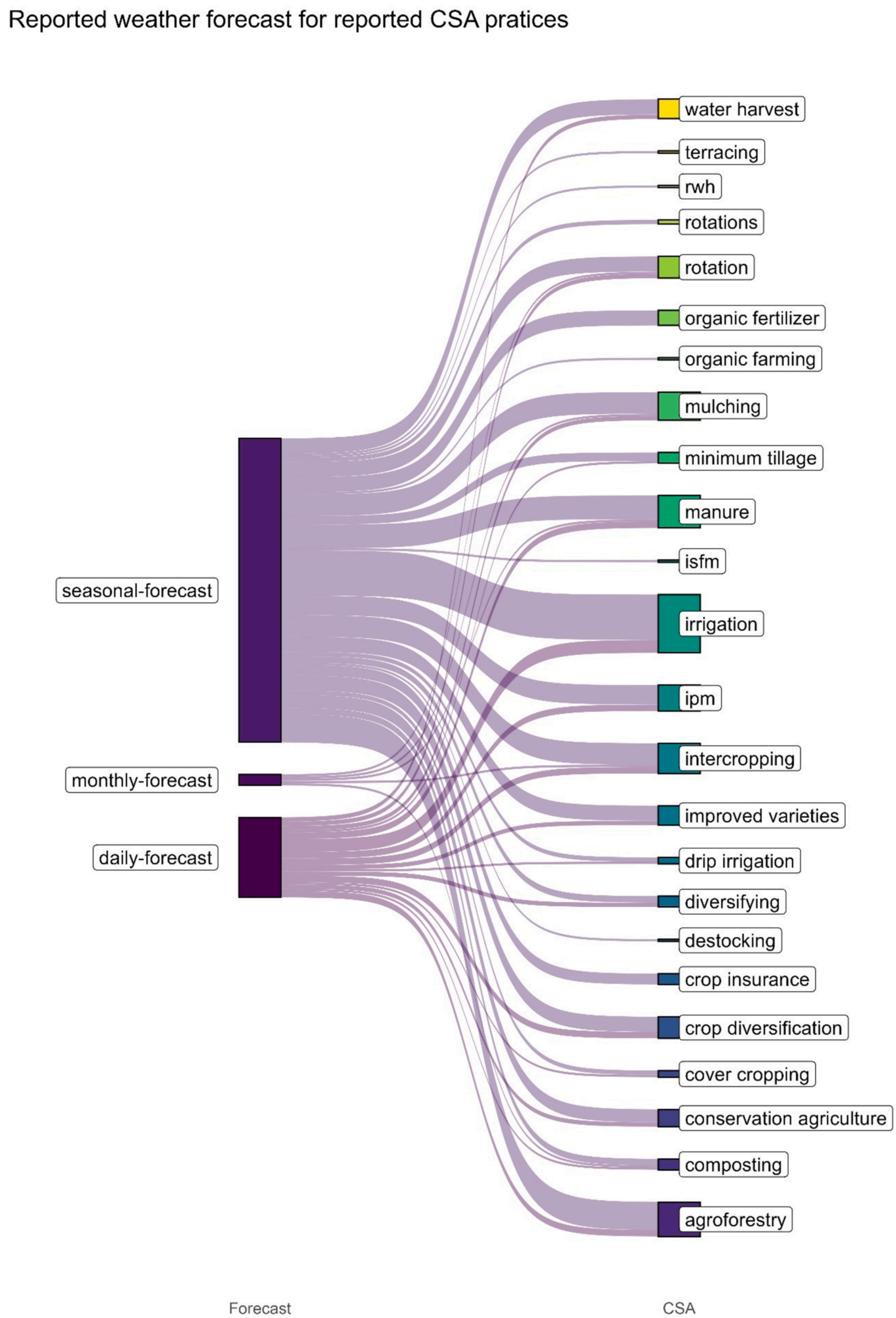

Fig. 4. Connections between Weather Forecast Types and Climate-Smart Agriculture (CSA) Practices. CSA: Climate-Smart Agriculture; ISFM: Integrated Soil Fertility Management; IPM: Integrated Pest Management and RWH: Rainwater Harvesting. The width of the lines in the Sankey diagram represents the frequency of mentions, indicating the reliance of each practice on the respective weather forecast type.

distribution, is often complemented by television and radio to aid in operational decisions like planting and irrigation scheduling. While less prominent, television and NGOs still play notable roles, especially in regions where visual and community-based communication are crucial.

Newspapers, SMS, farmer field schools, and field days are used less frequently but remain vital for localized and immediate dissemination. The diagram illustrates that most climate information services are shared through extension services followed by radio. By leveraging

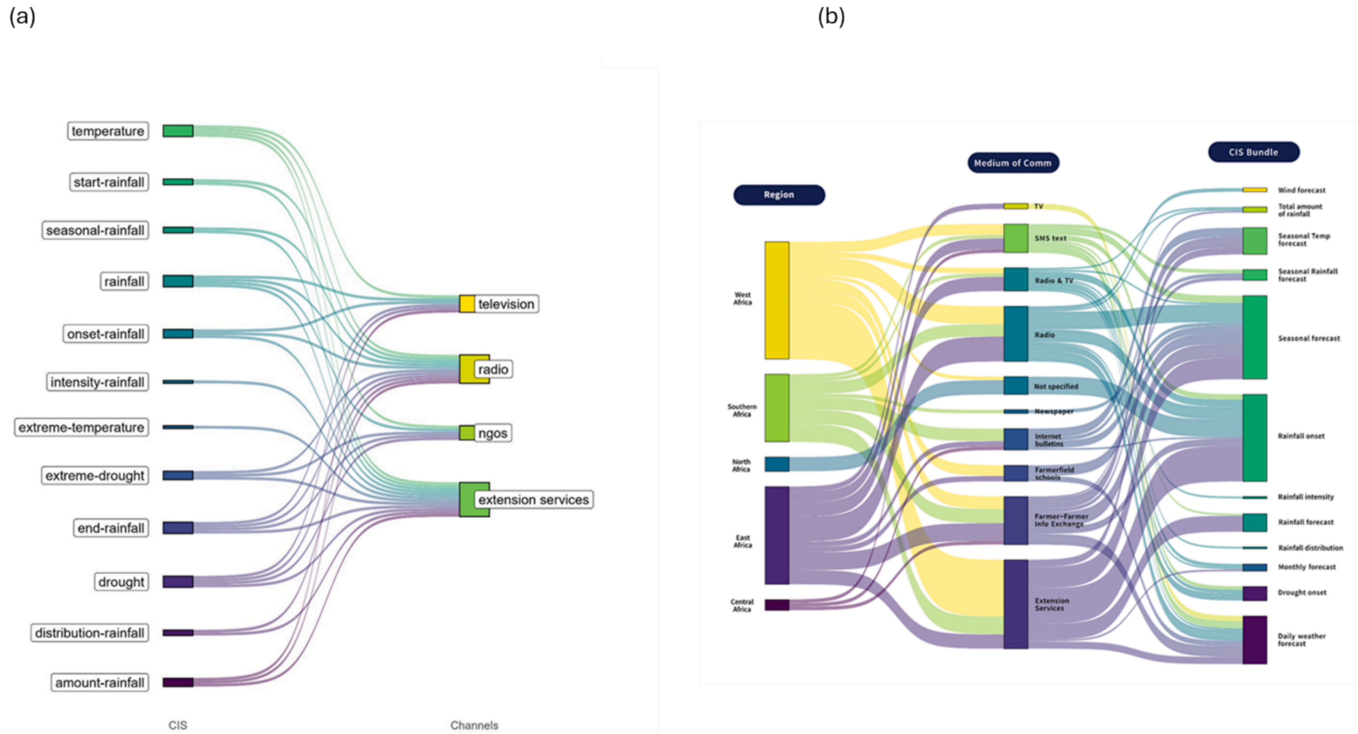

Fig. 5. (a) Connections between weather and climate information and the respective dissemination channels and (b) Disaggregated information dissemination according to geo-political regions in Africa. The disaggregation facilitates understanding of preferred communication media across the regions. Source: Authors.

diverse channels, the dissemination system ensures that critical CIS reaches a wide audience, enhancing resilience, productivity, and sustainability in agricultural practices across different regions. The results underscore the importance of an integrated approach for providing different types of CIS, which are needed to enable farmers to enhance resilience in the face of the multifaceted challenges of climate variability and change.

Fig. 5(b) provided a disaggregated and a more granular analysis of Fig. 5(a). Our interpretation of the Fig. 5b is as follows: West and East Africa provided the bulk of the data followed by southern Africa and lastly central and North Africa. Fig. 5b shows that each dissemination channel is unique and crucial in conveying climate information to farmers, ensuring a comprehensive and effective communication strategy that seeks to provide fit-for-purpose CSA interventions across scales. Due to data paucity in North and Central Africa, the discussion is limited to West, East, and Southern Africa. The supporting data for the assertions made are provided in Appendix 2 (Figure A2 – A four hierarchy sanky plot linking geo-political region to dissemination channel, WCIS bundle, and CSA practice) and supplementary material 2 (S2 – MS Excel Sheet).

West Africa

The dominant medium of communication was found to be extension services followed by radio. The subsequent and dominant weather and climate information bundle disseminated by both channels was rainfall onset. As alluded above, extension services are critical ensuring that farmers access ready to use weather and climate information for operational, tactical and strategic decision making across scales. We opine that the weather and climate information bundle was dominant because of potential association with length of growing season. Sivakumar (1988) found that early onset of rains resulted in longer growing season in the southern Sahel region. Rainfall onset information is critical for weather responsive crop management tactics (Sivakumar, 1988). West African monsoons are characterised by extreme wetting and drying period, thus we also opine that rainfall onset provides a general seasonal forecast and understanding of what to expect between extreme wet and dry seasons. During wet seasons, farmers resort to RWH for supplemental irrigation during the Harmattan period, whilst a late rainfall onset that results in a shorter growing seasons and farmers adopt improved crop varieties and resort to manure or composting which thrives under extreme heat conditions. In the West African scenario, RWH was prominent suggesting that the disseminated matched WCIS the adaptation intervention.

East Africa

The region equally disseminated weather and climate information via, extension services, farmer-to-farmer information exchange, and through radio. The respective disseminated weather and climate information bundles were rainfall onset and seasonal forecast, and drought onset. The subsequent CSA practices were RWH, adjusting planting dates, and intercropping (East Africa is characterised by two rainy seasons namely the long rains (Masika) and the short rains (Vuli) that result from biannual equatorial passage of the Intertropical Convergence Zone (Nicholson, 2017). For both instances. Surprisingly, daily weather forecast communicated through radio was dominant in East Africa and the dominant subsequent CSA practice was intercropping. Ideally, we expected the information to be of benefit to nomadic pastoralists to minimise distance travelled in search of watering points and fertile pastures. Therefore, we opine that WCIS should be tailored not only for crop production but also for livestock production.

Southern Africa

Radio and extension services were dominant and they mainly communicated seasonal temperature and seasonal rainfall forecasts. As previously alluded, radio is efficient because of its wider reach to the resource constrained rural population and, extension services play an equally critical role in information dissemination. Subsistence mixed farming in southern Africa relies heavily on total seasonal rainfall and frequency of occurrence of dry spells (Winsemius et al., 2014), thus early dissemination through wider reach networks inform farmers on the appropriate adaptation strategies such as using drought tolerant varieties, adjusting planting dates, and potential rainwater harvesting for crop and livestock irrigation during lean periods. Additionally, solar irrigation is gaining traction in the region hence the WCI bundle proved to be fit-for-purpose as studies had a high mention of solar irrigation.

Summative discussion for the disaggregated information dissemination channel and the communicated weather and climate information bundle across the different geo-political regions: Extension services are pivotal, providing direct links between research and farmers, especially for operational and tactical management decisions. They help optimize planting schedules, manage water resources, and prepare for droughts by offering practical advice and guidance on climate-smart practices. Currently the average extension agent-to-farmer ratio ranges from 1:3,000 to 1:10,000, representing low capacity across the continent (Dirwai et al., 2024; AGRA, 2017), thus deliberate efforts are required for capacitation to match the farmer population. In localities were conventional extension is constrained and limited, experience from India has shown that e-extension platform called iKrishi revealed the fact that e-extension can greatly succeed if the WCIS services are bundled with other services such as early warning of pest and disease outbreaks, market situations, announcements and also a possibility of farmers to interact with experts in real-time (ICARDA, 2023). Political will and private–public partnerships (PPPs) to digitise agriculture through rehabilitating and upgrading digital infrastructure to overcome connectivity barriers and increasing access to reasonably priced digital technologies is key to increase access to WCIS advisory in smallholder farming settings in sub-saharan Africa (Choruma et al., 2024). Targeted and gender inclusive digital training programmes to both extension workers and farmers are also critical in addressing the digital gap and digital literacy to women and youth farmers (Choruma et al., 2024, Areal et al., 2020, Kikulwe et al., 2014).

Farmer-to-farmer information exchange, which we classified as a knowledge smart CSA practice, can catalyse indigenous and local knowledge systems and trust through which farmers interpret and communicate seasonal forecasts through inherited knowledge and shared experiences. Zvobgo et al. (2023) indicated the importance of shared experiences amongst farmers in Chiredzi, Zimbabwe, in interpreting climate variables for climate decision-making processes. Although it encounters the uncertainty surrounding its reliability, farmer-to-farmer interaction is an entry point for various communication mediums, so linked WCIS and CSA knowledge is easily accessible and can be streamlined with scientific evidence.

… by.

Television, through visual and auditory means, aids in educating farmers with weather forecasts and climate-related programs, helping them understand complex data. NGOs support community engagement and capacity-building activities, particularly for marginalized groups, offering tailored information and resilience-building strategies. Newspapers provide detailed coverage and analytical insights into climate trends, supporting long-term strategic planning and raising community awareness. SMS services deliver concise and immediate updates directly to farmers' mobile phones, ensuring quick responses to changing conditions. Finally, farmer field schools and field days offer hands-on, interactive learning experiences, fostering practical knowledge and community collaboration. This multi-channel approach ensures that critical climate information reaches a diverse audience, enhancing

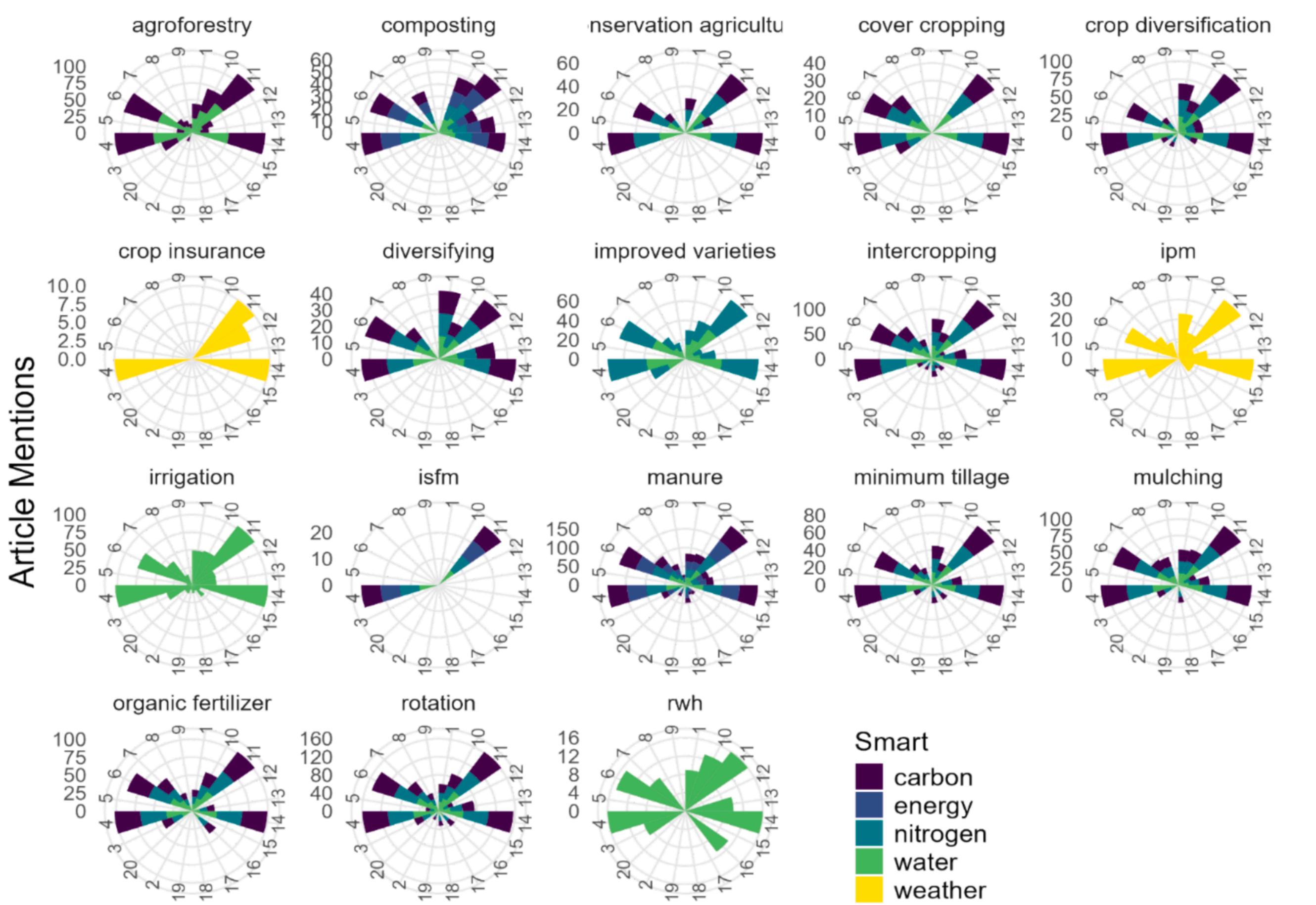

Fig. 6. Radial bar chart of climate information services mentioned for each CSA practice. Number 1–20 represent different weather variables with 1: amount-rainfall; 2: daily-rainfall; 3: distribution-rainfall; 4: drought; 5: end-drought; 6: end-rainfall; 7: extreme-drought; 8: extreme-temperature; 9: monthly-temperature; 10: onset-rainfall; 11: rainfall; 12: seasonal-rainfall; 13: start-rainfall; 14: temperature; 15: duration-rainfall; 16: intensity-rainfall; 17: onset-drought; 18: seasonal-drought; 19: maximum-temperature; 20: seasonal-temperature. Source: Authors.

agricultural practices' resilience, productivity, and sustainability.

Functional and operational Relationships between WCIS and CSA practices

Fig. 6 encapsulates the frequency of mentions of climate information services (CIS) associated with various climate-smart agriculture (CSA) practices as documented in the articles sourced. The CSA practices are displayed in a grid format, with each practice depicted in an individual radial chart, making the visualization comprehensive and easy to compare across different practices. The CSA practices covered agroforestry, composting, conservation agriculture, cover cropping, crop diversification, crop insurance, diversifying, improved varieties, intercropping, integrated pest management (IPM), irrigation, integrated soil fertility management (ISFM), manure, minimum tillage, mulching, organic fertilizer, rotation, and rainwater harvesting (RWH). Each radial bar within the charts represents the frequency of mentions for specific CSA practices, categorized into carbon (in dark purple), energy (in blue), nitrogen (in teal), water (in green), and weather (in yellow). The radial charts plot the frequency of mentions against a circular timeline denoted by numbers from 1 to 20, which correspond to specific types of climate information services listed at the bottom of the figure. These include various aspects of rainfall (amount, daily, distribution, onset, duration, intensity, seasonal, end), temperature (monthly, seasonal, extreme), drought, and other weather-related factors such as extreme drought and temperature.

The visualization (Fig. 6) reveals distinct patterns in how different CSA practices are associated with different types of climate information. Practices like irrigation and RWH show a significant association with water-related information services. In contrast, practices like IPM and crop insurance are more frequently linked to weather-related information. Agroforestry, composting, and conservation agriculture feature carbon-related information, denoted by the dark purple bars, suggesting a focus on carbon sequestration and related benefits. Furthermore, some practices like minimum tillage, organic fertilizer, and ISFM show a balanced distribution across multiple types of information services, indicating a diverse range of climate information needs. The diversity and density of the radial bars also highlight the multifaceted nature of CSA practices, illustrating how they integrate various aspects of climate information to enhance agricultural resilience and productivity.

Temperature

Seasonal temperature variations influence planting and harvesting times, crop and livestock selection, and overall agricultural planning. Aligning crop cycles with seasonal temperature patterns ensures optimal growth conditions and helps predict critical growth stages, such as flowering and fruiting. Monitoring these patterns aids in managing risks associated with temperature extremes. Monthly temperature data supports medium to long-term planning, helping farmers select suitable crop varieties and animal breeds and implement mitigation strategies like shading or mulching. Daily temperature is crucial for crop and animal management as it influences cumulative physiological processes, growth rates, and health. Monitoring daily temperature helps optimize planting and harvesting schedules, manage heat stress, and ensure optimal conditions for livestock, ultimately enhancing productivity and resilience in agricultural systems.

One strategy to retain or increase crop yields in future climates is to take advantage of developed cultivars with higher Growing Degree Days (GDD) needed to reach maturity to adapt to the increase in temperature (Onyeneke *et al.*, 2021; Magesa *et al.*, 2023) in regions where cold is a limitation to crop production, like in East and Southern Africa, an increase in temperature can extend the duration of the growing season. Using varieties with extended growing seasons may help farmers increase crop yields. However, extending the growing season may reduce water availability as crops mature due to prolonged active transpiration periods.

Rainfall

The amount of rainfall determines overall water availability, with adequate levels ensuring crops receive sufficient moisture for growth and yield. In contrast, insufficient rainfall leads to drought stress and excessive rainfall can cause flooding and soil erosion. The rainfall distribution throughout the growing season ensures consistent soil moisture, reducing water stress and enhancing crop yield. Uneven distribution can result in periods of drought and waterlogging, negatively impacting crop health (Onyeneke *et al.*, 2021; Bacci et al., 2023; Mbiafeu *et al.*, 2024). Rainfall intensity, which refers to the rainfall rate over a specific period, also plays a significant role. High-intensity rainfall can cause rapid runoff, leading to soil erosion, nutrient leaching, and reduced soil fertility. Moderate to low-intensity rainfall is preferable for better water infiltration and soil moisture retention. Understanding the onset of rainfall is essential for planning sowing and transplanting activities and optimizing crop establishment. Early prediction helps farmers adjust planting schedules and select appropriate crop varieties. Seasonal rainfall patterns are vital for crop planning, irrigation scheduling, managing water resources, and influencing decisions on crop varieties and planting dates. Daily rainfall data is crucial for short-term irrigation management, helping prevent waterlogging or drought stress and ensuring optimal crop growth and productivity.

Plausible linkages between WCIS and CSA concerning the scale of operation

Effectively bundling WCIS and CSA practices provides an enabling environment for optimizing operations across different spatial scales. For example, providing a seasonal rainfall forecast, the total amount of rainfall and seasonal temperature forecast can aid water managers at catchment and regional scale to make the following decisions:

(1) Design and implement improved water allocation for multiple water uses. This could also include the adoption at the catchment level of water-saving irrigation technologies, such as the alternate wetting and drying method for producing rice with less water (Dossou-Yovo and Saito, 2021),
(2) Shift to crops that require less water (short duration or drought tolerant varieties and species) and are heat tolerant in areas where heat stress has becoming common (Dossou-Yovo et al., 2022),
(3) Designing diversification programs for nomadic livestock pastoralists that will minimize distances travelled in search of pastures versus growing early development fodder based on the rainfall amount and temperatures

Thus, linking tailored WCIS to CSA for optimal resource use promotes natural resources, i.e. land and water utility valency for sustainable food supply. Table 3 shows the link between WCIS at variable temporal scales and CSA for strategic, tactical and operational decision-making. Borrowing from Fig. 6 (Radial Bar), different rainfall data (onset, distribution, intensity, duration, and end) can serve different purposes and influence the different CSA practices implemented across scales. Rainfall onset, seasonal forecast, and drought occurrence information bundles potentially improve and inform management practices such as drip irrigation and rainwater harvest techniques such as half-moon or zai pits, thus overall assisting farmers in defining their system needs and system potential. This provides a basis for the WCIS to be based on the scale of operation. For optimal utility, the WCIS should be tailored to cater to the different spatial scales ranging from field to country/region since CSA practices differ at each spatial scale.

As another example, high-level planning has a trickledown effect, i.e., proper catchment management based on evidence-based weather and climate information can positively influence irrigation and subsequent irrigation planning and scheduling at lower spatial scales such as farm, plot, and crop scales. Proper allocation based on the seasonal weather

Table 3
Plausible and innovative linkages between WCIS and CSA practices across multiple scales.

		Selected relevant WCI Bundle (Strategic, Operational and Tactical)				
*Scale and Indicative size in m^2	Description based on typical CSA practice	Daily forecast	Weekly	Monthly	Seasonal	Considerations
Crop ($< 10^0$)	Agro-ecological techniques, ISFM, manure/composting, RWH (e.g. zaii pits)	exT, R	exT, R	mT, onR	DR	• Since vertical water fluxes influence this scale, seasonal temperature and rainfall onset prepare farmers for rainwater harvesting (RWH) and implementation measures to minimize water loss through bare soil evaporation and evapotranspiration. • Seasonal rainfall forecasts and the onset of rain allow the farmers to adopt drought-tolerant breeds and/or shift planting dates to mitigate crop failure. • SWC techniques allow RWH to adopt improved seeds (early and drought-tolerant varieties). Shifting planting dates can be a viable option. • Total amount of rainfall facilitates planning for optimal irrigation schedules. • Temperature forecast allows water users to account for potential losses under open channel flow canal systems. • Total rainfall forecast can facilitate planning allocations for the lower scales. • Temperature forecasts can assist in determining water losses through evaporation and making the necessary adjustments. For example, minimizing allocations can influence CSA practice at the Irrigation system scale. Thus, farmers at the irrigation system scale can adjust by practising deficit irrigation techniques. • The WCI bundles inform water allocations to meet irrigation and energy production demands for food production. • Tailored WCI bundles facilitate the WEFE nexus approach to resource utilization. scales
Field (10^2 – 10^4)	Hybrid seeds, shifting planting days, SWC, crop rotations, and cover crops, precision farming/minimum tillage, intercropping, organic fertiliser, mulching, cover crops, intercropping	exT	exT, distR	mT, onR, distR, intR	DR, FL	
Farm (10^4 – 10^6)	SWC, precision farming/minimum tillage, crop insurance, organic fertiliser, RWH, mulching, mulching, cover crops, intercropping, Hybrid seeds	exT	exT	onR, distR, intR	DR, FL, enR, exDR, distR, intR	
Irrigation Systems (10^2 – 10^7)	Irrigation scheduling and water governance techniques (licensing, rules, by-laws, etc.)			mT, R, DR, FL	DR, FL	
Catchment (10^7 – 10^{10})	Optimized allocations through catchment management authorities			DR, FL, distR, intR	DR, FL, exDR	
Region/ Country (> 10^{10})	Legislation that guides water allocation for multi-use cases such as irrigation, energy production, etc.				DR, FL, exDR distR, intR,	

T, R, distR, enR, intR, onR, SR, W, DR, exDR, FL, exT = monthly Temp, rainfall, Rainfall distribution, end-rainfall, rainfall intensity, onset Rainfall, solar radiation, wind speed, drought, extreme Drought, flood, extreme Temp.
* Scale definitions adopted from Uhlenbrook et al. (2022). SWC = Soil and Water Conservation.

forecasts at the catchment scale considers losses experienced at each lower spatial that can be assumed to be recycled back into the ecosystem as environmental flows and inform the selection of land use, crops and varieties as well as water-harvesting measures thus adding an ecosystem component to the nexus farm management approach.

WCIS and CSA link as a mechanism for improved adaptation and mitigation

Linking WCIS to CSA practices is necessary to minimise crop failure and yield penalties and improve vertical diversification, including livestock production and the subsequent rangeland management. Improving access and the quality of WCIS information available to farmers allows them to adjust accordingly and adopt appropriate climate adaptation and climate mitigation efforts.

Roudier et al. (2016) studied how forecast influenced yield gain amongst millet growers in Niger. Participatory Integrated Climate Services for Agriculture (PICSA), reported by Clarkson et al. (2019) benefited 500 farmers in Rwanda and 7000 farmers in Northern Ghana. PICSA is a toolset farmers use to determine the best CSA practice depending on the local weather and climate. Another study by Diouf et al. (2020) investigated the benefits of using WCIS for informing the appropriate CSA practices, and they revealed that both genders that utilized WCIS in the form of seasonal forecasts for determining the best CSA management practices had a net yield gain range of 140 $kg.ha^{-1}$ to 158 $kg.ha^{-1}$. Djido et al. (2021) asserted that access to WCIS improved agricultural water management practices among farmers in Ashanti, Bessah et al. (2020) asserted how WCIS improved the adoption of CSA practices. However, extra support was needed to improve access (Naab et al., 2019).

Arouna et al. (2021) and Amoussohoui et al. (2023) reported how the RiceAdvice digital application enabled farmers access to information about the appropriate timing for cultivating rice, the varieties and the fertilizer management, which translated into an increase in farmers yield and income.

Developing, optimising, and leveraging existing decision support tools can benefit social innovation that improves and increases access to WCIS and the related CSA practices and promotes equitable growth across SSA smallholder and small-scale food systems. In instances where digital access is limited, it is imperative to leverage indigenous and local knowledge systems (ILKS) and mainstream them in modern science for improved adaptation. For example, Indigenous and local fertility management and land preparation programs can be linked to rainfall onset to improve (1) soil water holding capacity and (2) the extent of deep bed farming based on the precipitation threshold, which promotes deep percolation for groundwater recharge and potentially shallow bed streams for rainwater harvesting. For pastoralists, wind daily temperature and wind forecast can be utilised for rangeland management to assist potential veld fire risks and build anticipatory countermeasures for livestock feed.

Innovative Matching of WCIS to CSA practices

Climate change vulnerabilities differ across the farming landscape of Africa; hence, weather and climate information bundles need to feed into the heterogeneous vulnerabilities experienced by farmers across different scales. Also, farming typologies and CSA practices vary. Thus, this calls for innovative methods that link WCIS and CSA practices across scales holistically. This study, therefore, sought to provide a guiding framework for operational, strategic and tactical pathways for effective generation and provision of a fit-for-purpose WCIS bundle that will inform the ideal CSA interventions for minimal crop failure and yield penalties (Fig. 8). Identifying the farming typology and the gender, institutional and governance dynamics in the theatre of activity facilitates targeted interventions in the form of coordinated policy formulation and subsequent financing options for improved asset ownership. This provides the requisite operational ecosystem for effective adaptation and mitigation support. The integrated approach details the ideal intersection of the identified themes for strategic, operational, and tactical decision-making across different scales.

Linking WCIS and CSA practices and Operationalizing the framework

The study sought to identify the vulnerabilities, climate drivers, and potential CSA applications. The idea was to highlight key considerations and drivers linking WCIS and CSA (Fig. 8), as outlined in Table 3. Two categories, subsistence and commercial farming, were identified as the main farming enterprises. The enterprises were further characterized by the different pathways defined by the AU-IDAWM framework. For example, crops were provided for each farming category, with the commercial typology characterized by cash crops such as tea and sugar cane. The next entities detail the potential climate vulnerabilities and the effects likely to be encountered by the two farming enterprises.

The Affected CSA practices row next row provides information on the potentially affected CSA practices, followed by the weather and/or climatic conditions that put the target CSA practice at risk. The last two rows provide information on bespoke interventions, i.e., relevant weather and climate bundles that allow farmers to mitigate and adapt accordingly if provided. For example, a tea farmer primarily prefers daily temperature and humidity information in the commercial enterprise to determine the chill units (frost) that might affect the crops. Another example is how a P2 farmer in an irrigation scheme might value flood information to build climate-resilient water conveyance and application infrastructure. At the field scale, it is important to provide rainfall onset (dates associated with a critical amount of precipitation)

Framework on linking WCIS to CSA for regionally differentiated and contextual operationalization across multiple scales

Relevant questions and Arguments

	Typology at the Scale of Operation	WCIS Topic to be Addressed	CSA Issue to be Addressed	Integrated Approach	Argument
Governance	• Does the operating environment recognize regional and national policies' horizontal and vertical coordination, i.e., recognition of the different farming typologies? • What are the IT policies of various countries for internet and data coverage?	What is the existing national policy framework on WCIS?	What is the existing national policy framework on CSA?	Policy coherence between regional objectives and national initiatives.	Bottom-up approaches facilitate the seamless integration of regional and national policies by leveraging national resources and existing programmes.
Institutions	• Are there supporting institutions that recognize the existence of the multi-pathway smallholder farming systems? • What is the status and extent of involvement of the private sector in reaching out to the different farming typologies? • Are there existing partnerships among different ministries for a digital agricultural transformation?	• What active institutions are involved in generating, packaging and disseminating the context-specific WCI bundles? • Is there alignment amongst institutions for the packaging and disseminating contextualised weather and climate forecasts?	What institutions are involved in designing, validating and scaling climate-smart practices?	• Knowledgeable institutions that package fit-for-purpose bundles CSA and WCIS. • Alignment amongst different public and private institutions that package fit-for-purpose knowledge bundles across scales.	Capacitated institutions identify the major farming typologies and the potential risks affecting each one. This facilitates dialogues on identifying important and relevant weather and climate bundles for each CSA category at different scales.
Gender & Social Inclusion (GES)	• Are cultural norms compatible with the existing AU-IDAWM pathways? • Are there any capacity development mechanisms engaging women and youth?	• Does the information packaging acknowledge cultural and gender diversity? • Are there IT policies that intentionally target the marginalized and vulnerable women and youth in the operating environment?	Are the CSA practices compatible and inclusive, i.e., aligned with the socio-economic and cultural contexts and accommodative to avoid creating wealth and knowledge gaps?	Gender-sensitive and inclusive methods of CSA and WCIS information packaging and dissemination.	Disaggregating the gender and social dynamics across the different farming typologies allows for designing appropriate WCIS packages and information dissemination channels particularly fit for women and other disadvantaged groups.
Finance	Can transformational adaptation be applied to improve financing the different farming pathways outlined by the AU-IDAWM framework?	What WCIS bundle is financed and heavily disseminated through the various institutional information channels?	• What are the top most viable CSA options that can be financed? • What are the identifiable "low hanging fruit" / quick wins practices that can be financed for optimal adoption?	Finance for asset ownership. Asset ownership is categorized as tangible = mechanization and intangible = information. Intangible assets prioritize short-, medium-, and long-term adaptation options based on available WCIS and crops grown across scales.	Transformational adaptation facilitates private-public sector coordination for improved financing options. If financing institutions recognize and acknowledge the existence of the AU-IDAWM pathways, there is potential to facilitate financing the acquisition of tangible and intangible assets. Asset ownership.

Fig. 8. Framework on linking WCIS to CSA for regionally differentiated and contextual operationalization across multiple scales.

for farmers dependent on rainfall and utilizing water harvesting techniques such as Smart-Valleys (Dossou-Yovo et al., 2022) half-moon or zai pits (Fatondji et al., 2009) to correctly size (technical design) the in-field storage or rainwater harvesting facilities.

Innovative policies are needed to create an enabling environment for linking WCIS to CSA. This also requires collaboration across the various actors in data generation, application, translation, and dissemination. For example, the Participatory Integrated Climate Services for Agriculture (PICSA) (Clarkson et al., 2019) is an example of the collaborative use of WCIS to inform CSA practices. The PICSA model utilizes extension services, non-governmental organization (NGO) staff, and volunteers to train and provide information to farmers. Another example is the RiceAdvice digital application, which provided climate information, particularly the appropriate period for growing rice, rice varieties, and fertilizer management (quantity, timing, and mode of application).

Conclusions and recommendations

The study assessed how to link WCIS and CSA practices for optimizing CSA across multiple scales. The study concluded that:

i. Seasonal and daily forecasts are widely referenced, and they mainly inform CSA practices such as irrigation, integrated pest management, agroforestry and intercropping. Daily forecasts are used for immediate tactical decision-making, whereas seasonal forecasts inform high-impact decision-making that directs the agri-food enterprises,
ii. Climate information is mainly disseminated through extension services and radio platforms, as well as by non-governmental organisations and television. Extension services provide direct links between farmers and researchers, whilst radio broadly and rapidly disseminates temperature and drought information, making it accessible to even the most remote areas,
iii. The different CSA categories are tailored to different WCIS. Key climate variables such as rainfall and temperature can be disaggregated, for example, rainfall distribution/intensity, onset/start/end of rainfall and seasonal/extreme/monthly temperature, to inform the appropriate CSA practice

The study recommends identifying the farm typology in the locality and formulating the drivers for climate adaptation based on the current state of access to WCIS at scale. The study recommends identifying and mapping the local climate risks and vulnerabilities across the farming typology and customizing the WCIS bundles relevant to the typology. The study further recommends the following:

I. Policy recommendations centred on participatory and social inclusion are drivers for effective CSA adoption; a case in point is the Participatory Integrated Climate Services for Agriculture (PICSA),
II. Local and informal institutions should take centre stage to promote and push for acknowledging IK systems,
III. Indigenous knowledge systems should be integrated into mainstream climate technologies for effective WCIS generation and improved and bespoke CSA adoption,
IV. Digital e-extension platforms that provide WCIS and bundled services must be developed with a top-down (agency) and bottom-up (farmer and her crop/livestock) synergy, and
V. Political will and stakeholder collaborations are key in generating bespoke and regionally differentiated knowledge to improve WCIS and CSA linkages.

CRediT authorship contribution statement

Tafadzwanashe Mabhaudhi: Supervision, Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Tinashe Lindel Dirwai:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Cuthbert Taguta:** Writing – review & editing, Writing – original draft. **Aidan Senzanje:** Writing – review & editing, Conceptualization. **Wuletawu Abera:** Writing – review & editing. **Ajit Govid:** Writing – review & editing. **Elliott Ronald Dossou-Yovo:** Writing – review & editing. **Ermias Aynekulu:** Writing – review & editing. **Vimbayi Grace Petrova Chimonyo:** .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

Table A1
General definition of terms used in this study.

Term	Definition/Examples	References
Weather and climate information services	activities that generate and deliver climate data to support climate-resilient development and informed decision-making, covering variables like temperature, rainfall, and extreme weather	(UNECA, 2021).
Weather and Climate information (WCI) bundle	A forecast provided that influences a farmers decision making process. The bundle could comprise of one or more essential climate variable	Ardil (2021)
*Strategic decision making	Long term, high level decisions that determine the overall objective of a farming enterprise. For example, product innovation and long term CSA technology adoption and resource planning	
*Tactical decision making	Mid-term adaptive and flexible decisions that are seasonal and they support strategic goals. For example, implementing CSA practices for the season.	
*Operational decision making	Short term horizon decisions that govern day-to-day farming enterprise operations.	

*All definitins have been adjusted to fit context.

Appendix 2

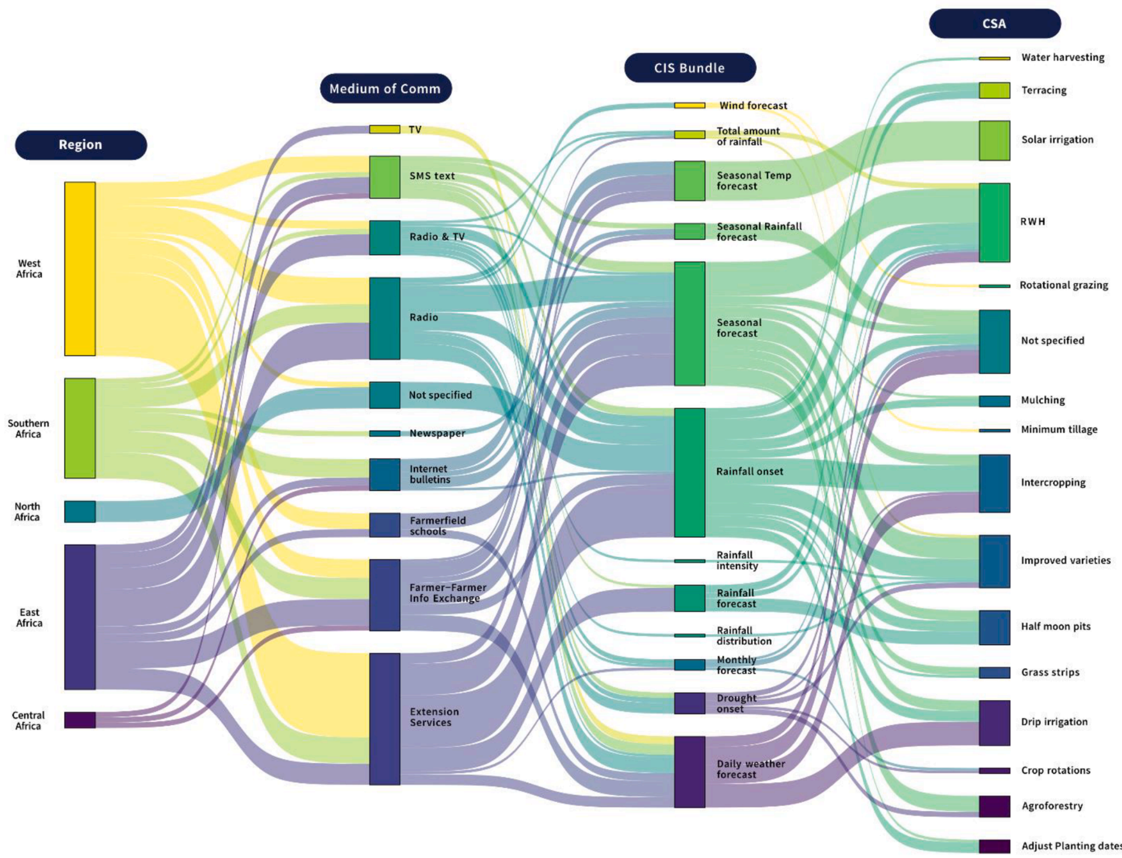

Fig. A2. A four hierarchy Sankey plot linking geo-political region to dissemination channel, WCIS bundle, and CSA practice

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2024.100529.

Data availability

Data will be made available on request.

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