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Bridging agronomy and extension: Enhancing farmer decision-making through climate-smart, data-driven advisory systems

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Abstract
Climate change, limited resources, and the need for sustainable practices are making it harder for agriculture to be productive and for people to have enough food. This review article looks at how climate-smart, data-driven advisory systems can help farmers make better decisions by connecting agronomy research with farm-level extension. We talk about the ideas behind climate-smart agriculture (CSA), which aims to boost productivity and resilience while cutting down on greenhouse gas emissions. We also talk about how digital tools and big data can help with decision-making for different types of cropping systems. Modern advisory platforms can give you exact advice on crop choices, planting schedules, irrigation, pest control, and more by combining real-time weather and field data with agronomic knowledge. This article looks back at how agronomy and extension have changed over time, focusing on the scientists and policies that helped shape new ideas in farming. We describe the most important parts of a good advisory framework, such as sensors, algorithms, communication channels, and training modules. We also show tables of CSA practices, data technologies, system components, and implementation challenges. Finally, we talk about the pros and cons of using these kinds of systems and come to the conclusion that a collaborative approach that combines technical innovation with on-the-ground extension is necessary to move forward with climate-resilient, sustainable agriculture for all types of crops.

Keywords: Agronomy, agricultural extension, climate-smart agriculture, decision support systems, data-driven advisory, precision agriculture, climate adaptation

Introduction
Farmers all over the world are facing more and more problems as climate change, extreme weather, and limited resources make farming systems less stable. If not planned for, declining soil health, irregular rainfall, rising temperatures, and severe storms can greatly lower crop yields [8]. At the same time, there are more people in the world, which means more people need land. Farmers have to make important decisions in this uncertain situation, often with little time and information about what and when to plant, how much water and fertilizer to use, and how to keep their crops safe from pests and disease. To make these choices well, you need to combine what you know about crops and the weather with what you know about each farm in detail [19]. Agronomy, which is the science of growing crops and taking care of soil, can help you make these decisions by giving you research-based answers [92]. To come up with better ways to farm, agronomists look at things like plant genetics, soil chemistry, water use efficiency, integrated pest management, and more [41]. For instance, agronomic research can find crop types that grow well in a certain area or can handle stress, or it can find the best planting densities and fertilizer schedules to get the most out of the land and resources. But just knowing the science isn't enough; it needs to be turned into useful advice that works for each farm's situation, resources, and culture [31].

This important link between agronomic research and the farmer's field is made possible by agricultural extension services. Extension agents, teachers, and field technicians turn research results into useful advice by doing demonstrations, field days, and training workshops on farms

[57]. In the past, extension has used face-to-face meetings, farmer group meetings, radio broadcasts, and printed pamphlets to share best practices. In many cases, these methods have worked. For instance, extension programs helped people in Asia and Latin America quickly adopt new crop varieties and methods during the Green Revolution. But traditional extension often doesn't work as well because of a lack of resources. There might only be one extension worker for every thousand farmers, and the advice they give might not be very specific to the situation [73]. In the last few years, information and communication technologies have started to change how agricultural knowledge is shared. Now, mobile phones, the internet, and community radio make it easier and faster to share information [93]. Farmers can get information about market prices, weather forecasts, and crop tips online, and often in their own language. There is still a gap between the wide range of agronomic research and the specific, day-to-day choices that farmers make, especially now that climate change has made things more complicated [20]. Data-driven advisory systems promise to help close this gap by giving farmers direct access to climate-smart agronomic knowledge. These systems use weather forecasts, sensor data, and scientific models to give you timely, location-specific advice [42]. In the next few sections, we will talk about the history of agronomy and extension, explain the basics of climate-smart agriculture, and look at how digital tools and analytics are used in farmer advisory services. Then we look at how these parts work together to help farmers make better decisions and figure out what technical and institutional factors affect the use of these systems [9]. This article shows how scientific research, extension outreach, and digital innovation can work together to create a strong framework for climate-resilient farming for all types of crops by giving a full review.

Historical Development and Key Pioneers

- Agronomy and agricultural extension have a long history of innovation that goes back hundreds of years. Early progress in agricultural science made it possible for modern methods to work. For example, in the 19th century, the chemist Justus von Liebig explained how nutrients help plants grow [32]. This set the stage for how we use fertilizers and manage soil fertility today. The seed drill, invented by Jethro Tull and others in the 18th century, made sowing more efficient and uniform. These early studies of soil chemistry and crop management are the basis for the agronomic rules we use today [58].
- By the end of the 1800s and the beginning of the 1900s, formal organizations for agricultural research and outreach started to appear. Universities and experiment stations looked into the crops and farming methods in different areas, and forward-thinking people pushed for farmer education [74]. For example, Seaman A. Knapp (1833-1911) was the first person in the United States to come up with the idea of a "demonstration farm," where farmers could see new methods in action on-site. His method was similar to the cooperative extension model [43]. The Smith-Lever Act, written by Hoke Smith and Frank Lever, was passed by American lawmakers in 1914. It officially set up the Cooperative Extension Service, which connected research done at land-grant universities with county extension agents. Many other countries later set up similar extension networks, making it a standard practice to teach farmers research-based methods [21].
- Advances in agronomy in the middle of the 20th century changed agriculture around the world. People often call Norman Borlaug the "father of the Green Revolution" [75]. He made wheat and rice varieties that were high-yielding and resistant to disease. Seed programs and extension efforts spread these varieties, which led to a huge increase in food production in the 1960s and 1970s [59]. Around the same time, other scientists made important discoveries. For example, Albert Howard's work on composting and organic soil management in the early 1900s predicted many ideas in sustainable agriculture, focusing on the long-term health of the land. These new ideas showed how powerful it is to connect scientific research with farmers who use it [33].
- The farming community has set new goals in the last few decades that focus on climate and sustainability. International groups and researchers came up with the idea of climate-smart agriculture (CSA) to deal with global climate change. CSA combines adaptation and mitigation into agronomy, focusing on methods that make crops more resilient to shocks and lower greenhouse gas emissions [76]. Scientists from places like the Food and Agriculture Organization (FAO) of the United Nations and different crop research centres have helped make CSA principles official and encourage their use. At the same time, tech pioneers have set the stage for data-driven extension. For example, the first generation of precision agriculture and decision-support tools came about in the late 20th century thanks to satellite imagery, GPS-guided farm equipment, and powerful computers [77].
- To sum up, the history of farming innovation is marked by ongoing cooperation between science and practice. Early scientists set the stage for understanding crops and soils. Pioneers in extension then came up with ways to share and use this information [60]. Later generations built on these ideas to solve problems with productivity and sustainability around the world. Remembering the work of past innovators and institutions helps us see how useful today's integrated advisory frameworks could be [78]. Climate-smart, data-driven advisory systems are the most recent step in this evolution. They build on the long history of bringing agricultural science to the field, but now with the help of digital technology [10].

Climate-Smart Agriculture: Principles and Practices

Climate-smart agriculture (CSA) is an approach that seeks to sustainably transform agricultural systems in the face of climate change [79]. It emphasizes three main objectives, often called the three pillars of CSA:

- **Increased Productivity:** Boost crop and livestock yields and farm incomes without exhausting natural resources. This ensures food security and economic gain for farmers [61].
- **Enhanced Resilience (Adaptation):** Strengthen the capacity of farms and communities to withstand shocks and stresses such as droughts, floods, heat waves, and pest outbreaks [44].
- **Climate Mitigation:** Reduce greenhouse gas emissions (e.g., from fertilizer use and livestock) and increase carbon sequestration (e.g., in soil and biomass) through sustainable practices [34].

CSA practices aim for a "triple win" by working towards these connected goals that help farmers, communities, and the environment. Increasing productivity helps meet the rising demand for food; resilience measures make people less vulnerable to extreme weather; and mitigation efforts help meet global climate goals [1]. To use CSA, you need to adapt your strategies to the specific agro-climatic conditions and farming systems in each area. What works in one area or crop may not work in another.

Many farming methods are called "climate-smart" because they help one or more of these pillars without hurting other areas. For instance, conservation tillage (leaving crop residues on the soil surface) keeps moisture in the soil (making it more resistant to drought) and adds organic matter to the soil (lessening the effects of climate change) while keeping yields the same [62]. Crop rotation (growing different crops in different seasons) and crop diversification (growing different crops at the same time) can make the soil more fertile and stop pest cycles. This way, if one crop fails because of bad weather, the risk is spread. Agroforestry systems, which mix trees or shrubs with crops, protect against wind and provide shade (resilience), store carbon (mitigation), and give farmers more ways to make money (productivity) [45]. Precision irrigation methods, like timed watering or drip irrigation, make sure that water is used efficiently. This directly addresses the problems caused by water scarcity and increases yields.

Many climate-smart practices depend on being precise and on time. For example, good scheduling of irrigation makes sure that crops only get water when they need it [22]. The picture above shows an irrigated field with straight, well-spaced rows. This shows how targeted water delivery can cut down on waste [80]. In real life, a field like this might use soil moisture sensors or satellite data to figure out the best time to water, which would save resources and help crops grow. In the same way, planting a cover crop during the off-season (like legumes after cereals) can add nitrogen and organic matter to the soil for the next cash crop. These methods use both traditional knowledge and scientific knowledge to make systems that last longer [11].

Table 1: Examples of Climate-Smart Agricultural Practices and their Benefits [90, 12, 15]

Practice	Description	Key Benefits
Conservation Tillage (No-till)	Leaving crop residues on fields with minimal plowing	Reduces soil erosion, conserves moisture, and enhances soil carbon
Cover Cropping	Planting cover crops (e.g., legumes) between main crops	Improves soil structure and fertility, suppresses weeds and erosion
Crop Rotation & Diversification	Alternating different crops or varieties in sequence	Breaks pest and disease cycles, improves soil health, spreads economic risk
Agroforestry	Integrating trees or shrubs with crops and/or livestock	Provides shade and shelter, improves soil fertility, and sequesters carbon
Integrated Pest Management (IPM)	Combining biological controls, cultural practices, and minimal chemicals	Minimizes pesticide use, manages resistance, and protects beneficial insects
Water Harvesting & Efficient Irrigation	Techniques like rainwater capture and precision irrigation	Ensures water availability during dry spells, improving drought resilience
Drought/Heat-Tolerant Varieties	Growing crop varieties bred for resistance to stress	Maintains productivity under extreme conditions and reduces yield loss
Integrated Nutrient Management	Balanced use of organic and inorganic fertilizers	Optimizes plant nutrition and improves soil fertility sustainably
Intercropping	Growing multiple crops together on the same field	Increases resource use efficiency, reduces pests, and diversifies farm output
Precision Irrigation (Drip, etc.)	Targeted watering systems that apply water directly to plant roots	Saves water, boosts yields, and prevents overwatering or salinity
Soil Mulching	Covering soil with organic (straw) or inorganic (plastic) mulch	Conserves soil moisture, moderates temperature, and suppresses weeds
Biofertilizers & Green Manures	Using beneficial microbes or nitrogen-fixing cover crops	Adds natural nutrients, improves soil health, and reduces synthetic fertilizer use
Climate-informed Planting Schedules	Timing planting dates based on long-range weather forecasts	Avoids crop loss from weather extremes and optimizes the growing season
Controlled Traffic Farming	Restricting heavy machinery to fixed lanes	Reduces soil compaction and preserves soil structure
Renewable Energy (e.g., solar pumps)	Using clean energy (solar, wind) for farm operations	Cuts emissions, lowers energy costs, and improves overall sustainability

These examples show how agronomic practice can be changed in many different ways to make it more resilient to climate change. The specific set of practices used on each farm depends on the crops grown, the weather in the area, and the farmer's goals [12]. For example, in a dry area, water-saving methods like drip irrigation and mulching may be more important, while in a wet area, drainage improvements or flood-tolerant plants may be more important. Farmers can use decision-support systems to help them choose and combine the best practices [2]. For example, they can use seasonal climate forecasts to change when they plant or which varieties to use. Using more than one CSA practice at the same time often has synergistic effects that increase productivity and sustainability even more [35].

Data-Driven Advisory Systems for Farmers

Modern advisory systems use a lot of different technologies and data to help farmers make decisions. These systems gather data about the environment and the farm, run it through analytical models, and give users useful suggestions [81]. Some common data inputs are:

- **Weather data:** Current and predicted weather data from satellites and ground stations [82].
- **Remote sensing:** Images from satellites or drones that show the health of crops, the amount of vegetation cover, or the stress on water (often using indices like NDVI) [83].
- **Soil and in-field sensors:** These are devices that measure moisture, temperature, nutrient levels, and other important factors right in the field [46].
- **Farm management records:** Information that farmers enter about when they plant, what kinds of crops they grow, how much they use of each input, and how much they get in return [84].

- **Market and socio-economic data:** Information about local prices, input costs, and policy or market trends that have an effect on profitability [23].

After that, this data is used with analytical tools like crop simulation models, statistical forecasting, and machine learning algorithms. A model could, for instance, use current soil moisture readings and a weather forecast to figure out if there is a chance of drought stress and send an irrigation alert [63]. Or a machine learning tool could look at past yield and weather data to make better fertilizer suggestions. The most important thing is that these models use agronomic knowledge in situations that are always changing [13].

On the farmer's side, though, many people get advice through cell phones or other simple ways of communicating. A farmer looks at a fruit orchard in the picture above while using a smart phone app. This example shows how digital tools can work with fieldwork. The farmer could get alerts through an app or a text message, such as "Frost expected in 3 days, delay planting" or "Apply biofertilizer now to boost soil nitrogen" [47]. In the same way, extension agents can use tablet or web dashboards to keep an eye on regional data and give advice to several farmers at once. This kind of mobile and SMS-based advice is becoming more common, especially in rural areas where smart phone use is growing quickly [3].

Table 2: Key Data Sources and Technologies for Climate-Smart Advisory [48, 85]

Data/Technology	Use/Application	Impact/Examples
Satellite Imagery	Remote sensing of vegetation and soil conditions over large areas	Enables monitoring of plant vigor, water stress, and pest damage across regions; supports early warning systems
Weather Station Networks	Local sensors measuring temperature, rainfall, humidity, and wind	Supplies ground-level climate data for local forecasts and advisories (e.g. planting dates, frost alerts)
Soil Sensors	In-field devices measuring soil moisture, temperature, and nutrients	Allows precise irrigation and fertilization scheduling based on actual soil conditions
Drones & UAVs	High-resolution aerial imaging of specific fields	Enables detailed crop scouting, mapping field variability, and targeted interventions (e.g. spot-spraying)
IoT & Smart Devices	Internet-connected sensors and controllers (e.g. automated irrigators)	Automates continuous data collection on weather, soil, and equipment use, feeding real-time analytics
Climate Models & Forecasts	Numerical models predicting seasonal and long-term climate trends	Guides strategic planning such as crop choices and planting schedules under projected conditions
Big Data & Analytics	Processing and analyzing large volumes of agricultural data	Identifies trends and relationships from combined weather, soil, yield, and socio-economic data
Machine Learning & AI	Algorithms that learn patterns from historical and real-time data	Improves prediction of yields, pest/disease outbreaks, and optimal management actions through advanced analytics
Mobile Apps & SMS Services	Smartphone applications and messaging platforms for farmers	Delivers weather alerts, advisory messages, and market information directly to farmers in real time
GIS & Digital Mapping	Geographic Information Systems for spatial analysis	Visualizes farm locations, soil maps, and risk zones to optimize land use and resource allocation
Farmer Surveys & Crowd sourcing	Gathering observations and feedback directly from farmers	Incorporates local knowledge and ground truth to refine advisories and improve model accuracy
Market & Supply Data	Information on crop prices, supply levels, and demand trends	Informs production and marketing decisions by aligning crop choices with market opportunities
Knowledge Databases	Repositories of agronomic research and best practices	Ensures that advisories reflect the latest scientific findings and locally adapted techniques
Blockchain & Traceability	Distributed ledgers for recording farm inputs and outputs	Enables product traceability and quality assurance, which can incentivize sustainable practices
Cloud Computing	Remote servers for data storage and analysis	Supports scalable, multi-user advisory platforms accessible from anywhere with internet

The infrastructure of an advisory platform is made up of these data sources and technologies. For instance, a system might use satellite rainfall estimates and ground temperature readings to run a model of how crops grow. This model would then predict how wet the soil will be and what stage the crops will be at [64]. A decision engine could turn those predictions into specific advice, like "apply 50 kg/ha nitrogen in two weeks" or "plant in five days to avoid a dry spell." Machine learning can make this process better by changing the model parameters based on what happens. Importantly, these systems can change extension from just reactive guidance to proactive, ongoing support [14].
Recent pilot projects show how helpful data-driven advisories can be. Farmers who used a soil moisture sensor network and an irrigation scheduling app used up to 30% less water while still getting the same amount of crops. This was because they watered their crops at the best times [86]. In another instance, a weather-index advisory for smallholders mitigated crop losses by recommending that farmers postpone planting in anticipation of a predicted drought. These successes show how timely, site-specific advice based on agronomic science can boost both productivity and resilience at the same time [49].

- Bringing together agronomy and extension through digital advice to make good data-driven advisory services, agronomy, technology, and extension practice must all work together without problems [36].
- Working together across fields: Agronomists, data scientists, software engineers, and extension specialists need to work together. Agronomists turn biological processes into models, data scientists make algorithms, IT professionals build the platforms, and extension experts make sure that farmers can understand the results. This teamwork is just as important as the technology.
- Infrastructure for data: We need strong data pipelines [50]. The system needs to get weather data from national meteorological services or global models, as well as satellite images and sensor feeds. Cleaning and standardizing the data makes sure that the models get the right information. Open-data projects and agreements between agencies (like

the weather, soil, and agricultural ministries) to share data make the information that is available better [24].

- Technology Platforms: Advisory systems usually have cloud-based servers that process data and run models, as well as front-end interfaces like mobile apps or web dashboards for users. Cloud computing is scalable, which means it can handle a lot of data and a lot of users. In places where the internet isn't always reliable, hybrid solutions may use local servers or sync up every so often to send updates without needing to be connected all the time [65].
- Integration of Extensions: Digital tools should add to, not replace, the human extension network. Training programs can teach extension workers how to use these tools and understand what the models say. Extension agents can give farmers real-world context, explain suggestions, and help them make changes. In some models, extension agents bring tablets with the advisory app on them to share information during farm visits [15]. This makes each agent a "mobile advisor" [66].
- Localizing Content: Even the best advice needs to be relevant to the area. Advisory systems often have parts that let you adjust recommendations to fit the needs of your area. For example, soil maps can be used to change the amount of fertilizer to use and data about the local climate zone can change the advice about when to plant [67]. Farmers can enter their own variety and management information so that the suggestions match what they really do. Getting farmers to take part in initial surveys or workshops is a good way to get this local information [51].
- User Accessibility: Advisory outputs must be easy for users to understand. When people can't read or write interfaces should be in their own language and use clear symbols or pictures. Using more than one delivery method can help you reach more people. For example, you could combine a smart phone app for younger or wealthier farmers with SMS alerts and even community radio announcements to get the word out to more people [37].
- Feedback Loops: Being able to get feedback is a key part. Farmers and agents should be able to tell what happened (like actual yields or pest outbreaks) or ask questions. You can use this information to make the system's suggestions better over time. Farmers help improve models by giving them real-world data, which means they are part of the learning loop. This participatory approach builds trust and makes the system more useful over time [25].

Table 3: Key Components of a Data-Driven Agricultural Advisory System [87, 91]

Component	Function/Role	Benefit/Impact
Data Collection	Gathering data from weather stations, satellites, field sensors, and farmer inputs	Provides the raw information needed for analysis and decision-making
Data Management & Storage	Organizing and storing collected data in databases or cloud storage	Ensures data is integrated, accessible, and maintained over time
Data Processing & Analytics	Cleaning, integrating, and analyzing data	Generates insights such as soil moisture trends, pest risk, and yield forecasts
Decision Support Engine	Algorithms or models that produce farm-specific recommendations	Transforms analytical outputs into actionable advice (e.g. irrigation timing, seeding rate)
User Interface (Mobile/Web)	Applications and websites for accessing advisories	Delivers information and dashboards to farmers and extension workers in an intuitive format
Communication Channels (SMS/Voice)	Messaging systems (text/voice) for advisories	Ensures even farmers without smart phones receive timely alerts via SMS or voice calls
Extension Agent Tools	Dashboards and apps designed for field officers	Enables extension staff to view aggregated data and advise multiple farmers efficiently
Feedback Mechanism	Channels (surveys, app reports, meetings) for user input	Allows farmers and agents to report outcomes and questions, improving system accuracy
Localization	Customization for language, culture, and local conditions	Ensures recommendations are understandable and relevant in each community
Training & Capacity Building	Farmer and agent education on using tools and practices	Empowers users to adopt new tools effectively and understand the advice given
Knowledge Update Module	Integrating new research findings and seasonal forecasts	Keeps advisories current with the latest agronomic knowledge and climate projections
GIS & Mapping	Mapping farm plots and spatial data analysis	Aligns recommendations with specific field locations, soil types, and microclimates
Monitoring & Evaluation	Tracking usage, adoption, and impact metrics	Measures system performance and outcome improvements to guide refinements
Data Privacy & Security	Protecting farmer data and system integrity	Builds trust by ensuring responsible handling of personal and farm data
Technical Infrastructure	Ensuring reliable internet, power, and hardware	Supports uninterrupted operation of advisory services, even in remote areas

These parts work together to make an integrated advisory platform. In reality, each country or region can build its own architecture [68]. Some governments have put money into national data portals and extension platforms. In other cases, non-profits or private companies have made mobile advisories that are specific to the needs of the area [16]. The most important thing is that each system accurately uses agronomic knowledge and extension techniques. For instance, a rule for deciding when to use fertilizer must be based on local research and tested in the field. Extension agencies often test and change digital advisories to make sure they really help farmers [26].

Enhancing Farmer Decision-Making

Effective advisory systems align closely with the key decisions that farmers routinely make. Typical decision categories include:

- **Crop and Variety Selection:** Choosing which crops or

cultivars to plant based on soil type, weather outlook, and market demand [52].
- **Planting Date and Density:** Deciding when to sow seeds and how densely to plant, to match the growing season and resource availability [69].
- **Water Management:** Planning irrigation schedules or rainwater harvesting to meet crop water needs efficiently [38].
- **Nutrient Management:** Determining fertilizer type, rate, and timing to match crop growth stages and soil fertility [88].
- **Pest, Disease, and Weed Control:** Selecting prevention or control measures and timing them for greatest effect [70].
- **Harvesting and Post-Harvest Handling:** Timing harvest and managing post-harvest steps to minimize losses and maximize quality [4].

A climate-smart advisory gives data-backed advice for each of these choices. For instance, think about a time when a drought is expected to happen. Based on past yield data and the weather forecast, the advisory might recommend planting millet that can handle drought instead of maize that needs a lot of water [71]. It might also suggest waiting a week to plant so that you can catch the early rains (timing), or using less nitrogen fertilizer than usual if heavy rain isn't likely (nutrient management) [53]. When combined with weather forecasts, soil moisture sensors can give you specific irrigation advice, like "apply 30 mm of water in 4 days," that saves water and keeps plants from getting stressed. The system can also send out a pest-control warning ahead of time if the weather is right for a fungal disease [27].

Each suggestion shows how to use real-time data to follow the best agricultural practices. Research indicates that when farmers adhere to customized guidance, efficiency is enhanced [72]. For example, precision irrigation based on advice often uses less water and gets the same or better yields. Alerts about pests that come at the right time can save a lot of crops that would have been lost. Even small changes, like moving the planting date back a few days, can have a big effect when the weather is unpredictable. These gains add up over time [17].

Farmers also make money. They can make more money per unit of input by using less expensive inputs like water, fertilizer, and chemicals [54]. The advisory gives them access to market data, which helps them pick crops that will give them the best return or decide when to sell their goods for the best price. In this way, data-driven advisories not only make things more technically sound, but they also help people make a living [5].

Challenges and Opportunities

Despite their potential, implementing climate-smart advisory systems involves overcoming several challenges. Table 4 summarizes key obstacles and strategies to address them. Notable challenges include:
- **Digital Divide:** Many smallholder farmers have limited experience with smart phones or computers, and some are illiterate or speak only local languages. To reach these farmers, systems must offer user-friendly interfaces and alternative channels. Training programs and participatory demonstrations can build digital skills. In practice, successful initiatives often use icon-based apps or voice-enabled services in local tongues to bridge literacy gaps [28].
- **Connectivity and Infrastructure:** Rural connectivity may be weak or absent, and electricity can be unreliable. Solutions include designing offline-capable apps that synchronize data when possible, and using SMS or radio to deliver advisories where internet is not available. Investment in rural broadband, community information centers, or local servers can also extend coverage. Mobile solar chargers and long-lasting devices help mitigate power issues [55].
- **Cost and Scalability:** Hardware (sensors, smart phones) and software development can be expensive. Public-private partnerships and subsidies can lower barriers. Open-source software and commodity hardware (e.g. using simple moisture sensors) reduce costs. Business models such as subsidized airtime or offering premium services (like precision forecasting) can make platforms financially viable. To scale from pilots, systems should be built modularly so they can be expanded or replicated in new regions without a complete redesign [39].
- **Data Quality and Coverage:** Reliable advisories depend on accurate data. Sparse weather stations or incomplete soil surveys can limit precision. Using crowd-sourced data (farmers reporting rain or yields via SMS) and high-resolution satellite data can fill gaps. Governments and organizations can promote open data initiatives, making meteorological and soil data publicly available. Quality control measures and calibration of sensors are also important [73].
- **Local Adaptation:** One-size-fits-all advice will fail in diverse environments. Customization is essential. This means calibrating models to local crop varieties, soil types, and farming practices. Extension agents can adjust generic outputs to suit field realities, or systems can allow user inputs for key parameters. Participatory approach engaging farmers in system design and feedback ensures the advisory is grounded in local knowledge and constraints [74].
- **Institutional Coordination:** Agricultural advisory often involves multiple actors: government agencies, research institutions, NGOs, and private companies. Without coordination, efforts can be fragmented. Establishing common platforms and data standards encourages collaboration. For example, a national agricultural data clearinghouse can ensure that researchers, extension services, and startups work from the same datasets. Clear roles and partnerships enable resources to be pooled and duplication avoided [18].
- **Socioeconomic and Equity Concerns:** There are disparities in access and benefit. Women farmers, young people, and the poorest may be left out without deliberate inclusion efforts. Designing tools with input from diverse user groups, ensuring gender-sensitive outreach, and providing shared community devices (e.g. one smart phone per village) can improve equity. Tailoring content and delivery to cultural contexts also promotes wider adoption [56].
- **Climate and Model Uncertainty:** All forecasts and models carry uncertainty. Farmers may be skeptical if advisories sometimes err. To manage expectations, advisories can present probabilistic guidance (e.g. “70% chance of dry weather”) rather than absolute predictions. Building trust requires transparency about uncertainty. Over time, as the system learns from outcomes (feedback loops), its accuracy improves, and farmer confidence grows [6].

Despite these challenges, opportunities are abundant. Mobile phone ownership continues to rise even in remote areas, and the cost of sensors and satellite data is falling. Many countries now include digital agriculture in their national strategies [30]. The private sector agribusinesses, telecoms, tech firms are increasingly investing in agri-data solutions. Farmer success stories can fuel wider interest: in several pilot projects, farmers using digital advisories have reported yield increases of 10-30% or substantial savings on inputs. These results can inspire neighbors and justify further investment [40].

To seize these opportunities, stakeholders must act together. Governments and donors can fund rural connectivity and extension training, and create enabling policies for data sharing [29]. Research institutions should develop and validate models for key local crops and conditions. Extension services should integrate digital tools into their workflows and seek continuous feedback from farmers. When technical innovation is matched with strong on-the-ground support and capacity building, the resulting advisory systems stand the best chance of success [7].

Table 4: Key Challenges and Strategies for Implementing Climate-Smart, Data-Driven Advisory Systems [89, 51]

Challenge	Opportunity/Strategy
Low digital literacy among farmers	Provide targeted training, user-friendly interfaces, and local demonstration events
Limited connectivity and infrastructure	Develop offline-capable apps and SMS/voice services; invest in rural internet and electricity
High costs of implementation	Use public-private partnerships, subsidies, and open-source tools to reduce barriers
Scarce quality data (weather, soil)	Employ crowd sourcing, deploy low-cost sensors, and utilize satellite/remote sensing data
Generic one-size-fits-all advice	Localize content through participatory methods, field trials, and region-specific models
Farmer trust and adoption barriers	Engage farmers in system design, share success stories, and build credibility via extension
Fragmented extension services	Coordinate agencies and integrate platforms to provide unified advisory services
Socioeconomic and gender disparities	Design inclusive tools (multilingual, low-cost) and ensure outreach to marginalized groups
Rapid climate variability	Use real-time monitoring and ensemble forecasts for adaptive, flexible advice
Language and cultural differences	Offer multilingual content, voice interfaces, and culturally appropriate messaging
Limited resources (power, devices)	Deploy solar power, shared devices, and community information hubs
Data privacy and security concerns	Implement clear data governance, encryption, and farmer consent mechanisms
Scaling pilot projects to wide use	Ensure modular, scalable design and secure stakeholder engagement
Sustaining user engagement	Provide regular updates, interactive features, and link advice to tangible incentives
Data interoperability issues	Adopt open standards and APIs for seamless integration across platforms

Conclusion

Climate-smart, data-driven advisory systems that connect agronomy and extension are a promising way to move towards sustainable agricultural development. These systems help farmers make better and more accurate decisions by combining strict scientific knowledge with real-time data and modern communication tools. Because weather forecasts, sensors, and agronomic models work together, farmers can make decisions about planting, watering, inputs, and pest control based on facts and predictions instead of guesswork. This has been shown to make different types of farming systems more resilient to climate shocks, increase yields, and lower input costs. In the past, progress in farming has always come from combining new ideas with old ones. Today, digital technology makes it possible to make that alignment even stronger than ever before. Extension workers with mobile apps can help many more farmers with personalized advice. Researchers can also get field data from thousands of farms to keep improving their recommendations. The end result is a cycle of learning that never ends: agronomy teaches extension, and extension teaches agronomy through feedback from farmers. To get the most out of this model, people from different fields need to work together. Policymakers ought to allocate resources towards rural connectivity and open data infrastructure, while also incorporating digital advisory into national agricultural strategies. Researchers and extension agents need to work together to make tools that are easy to use and based on local conditions. Farmers and communities should be seen as partners in the creation and testing of advisory services. Farmers can change with the times and keep their productivity up in a sustainable way when they get timely, localized advice based on good agronomic science. Data-driven advisory systems basically connect the lab to the land. By encouraging collaboration between different fields and giving farmers the information they need, we can set agriculture on a path that will be productive, strong, and smart for the climate for many years to come.

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