AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 03, Issue: 08 (August, 2026)
Available online at http://www.agrimagazine.in
©Agri Magazine, ISSN: 3048-8656

# Combining Weather Forecasts, Soil Moisture and Crop Phenology for Climate-Smart Agronomic Management

*Chandan Prasad, Dr. Argha Ghosh, Dr. Ipsita Kar and Dr. Anshuman Nayak
College of Agriculture, OUAT, Bhubaneswar, Odisha, India
*Corresponding Author's email: chandan140920@gmail.com

Agriculture has always depended on weather, water and the biological rhythm of crops. What is changing is the reliability of these factors. Rainfall is becoming more erratic, periods of intense heat are occurring more frequently, and the difference between a productive season and a difficult one can sometimes be determined by a few days of weather. Under such conditions, traditional agronomic decisions based mainly on fixed calendars are becoming less dependable. A crop does not need water simply because a particular day of the month has arrived; it needs water according to its growth stage, the moisture available in the root zone and the atmospheric demand for water. This article examines an integrated approach in which short-term weather forecasts, soil-moisture information and crop phenology are brought together to support field-level agronomic decisions. The central argument is that none of these information sources is sufficient on its own. Weather forecasts indicate what may happen, soil moisture shows what has already happened in the field, and crop phenology explains how important the expected conditions are for the crop at a particular stage. Their combination can therefore support more timely decisions on irrigation, sowing, fertilization, pest and disease management, drainage and harvesting. The article also presents a case study based on emerging climate-informed irrigation and agricultural advisory work in Odisha, India. The Darpanarayanpur Minor Irrigation Project has been identified as a pilot site for a Climate-Informed Irrigation Decision Support System that combines crop modelling, climate projections, remote sensing-derived phenology, soil information and water-allocation optimization. The discussion illustrates how such systems can move agricultural management away from fixed schedules towards dynamic, evidence-based decisions. The article concludes that climate-smart agronomy is not simply about installing sensors or developing sophisticated models. Its real value lies in converting diverse data into simple, timely and locally meaningful actions that farmers can trust and use.

**Keywords:** climate-smart agriculture, weather forecast, soil moisture, crop phenology, irrigation scheduling, decision support system, precision agriculture, Odisha, climate resilience, agronomic management

## Introduction

For generations, farmers have made decisions by observing the sky, feeling the soil, watching the crop and drawing on experience accumulated over many seasons. These observations remain valuable. However, climate variability is making some of the assumptions behind traditional farm calendars less reliable. The onset of rainfall can shift. A dry spell may arrive in the middle of what is normally considered a wet period. Temperatures may remain unusually high during a crop's reproductive stage. Heavy rainfall may occur within a few hours rather than being distributed over several days. These changes create a difficult management problem: farmers have to make decisions before they know exactly what the weather will do. This is where climate-smart agronomic management becomes important. Climate-smart agriculture is generally associated with three broad objectives: maintaining or increasing productivity, strengthening adaptation to climate risks, and, where possible, reducing greenhouse-gas emissions. Recent research also emphasizes that climate-smart agriculture cannot be treated as a universal package. Measures have to be adapted to local crops, soils, water availability, economic conditions and farmer priorities.

One promising approach is to combine three types of information:

1. **Weather forecasts**, which provide an indication of future rainfall, temperature, humidity, wind and other atmospheric conditions.
2. **Soil-moisture information**, which describes the water status of the soil and therefore provides a more direct indication of whether water is available to plants.
3. **Crop phenology**, which describes the developmental stage of the crop, such as emergence, vegetative growth, flowering, grain filling or maturity.

Individually, each source answers only part of the management question. A weather forecast may predict rainfall, but it does not tell us how much water is already present in the root zone. A soil-moisture sensor may show that the soil is dry, but it does not necessarily tell us whether rainfall is likely tomorrow. Phenology tells us that a crop is flowering, but it does not indicate whether sufficient water is available to support flowering. When the three are considered together, however, the question changes from *"What is the weather?"* to *"What should I do in this field, for this crop, at this particular stage, given the water already available and the weather expected over the next few days?"*

That shift is at the heart of climate-smart agronomic management.

## Why Conventional Farm Scheduling Is Becoming Less Reliable

Traditional agricultural recommendations often use fixed dates or generalized rules. Irrigate after a certain number of days. Apply fertilizer at a particular crop age. Spray when a particular calendar date is reached. Harvest within a conventional window.

Such recommendations are useful as broad guidelines, but they assume that the growing environment is reasonably predictable. Climate variability challenges this assumption. For example, suppose a farmer normally irrigates a rice field every five days. If 40 mm of rainfall occurs on the third day, irrigating according to the original schedule could result in unnecessary water use. Conversely, if the weather forecast indicates a prolonged dry period and the soil profile is already approaching a moisture-stress threshold, waiting until the fifth day could expose the crop to avoidable stress. The problem is therefore not simply a lack of information. It is a lack of **integrated information at the right time**. Research on agricultural seasonal forecasting has shown that farmers are interested not only in rainfall or temperature forecasts but also in derived information such as expected dry spells and other indicators directly connected to farm decisions. The timing, uncertainty and usability of forecasts are particularly important. This suggests that a useful agricultural information system should not merely tell farmers:

"Rainfall probability is 60%."

Instead, it should ideally translate the forecast into something closer to:

"The crop is at flowering, soil moisture is adequate today, and moderate rainfall is expected within the next 24-48 hours; irrigation can therefore be postponed."

The second message has much greater agronomic value.

## The Three Pillars of Integrated Agronomic Decision-Making

### Weather Forecasts: Looking Ahead

Weather forecasting provides the forward-looking component of the decision system.

For agriculture, rainfall is obviously important, but other variables also matter. Temperature influences crop development and evapotranspiration. Relative humidity affects disease risk. Wind speed influences evaporation and the feasibility of spraying. Solar radiation influences photosynthesis and crop water demand.

The usefulness of a forecast depends on its time horizon.

**Short-range forecasts**

Forecasts covering the next few days can support decisions such as:

- whether to irrigate;
- whether to delay irrigation because rain is expected;
- whether to apply fertilizer;
- whether spraying conditions are suitable;
- whether harvesting should be advanced;
- whether drainage arrangements are necessary before heavy rain.

India's Meteorological Department has increasingly moved toward location-specific agricultural advisories. Its KALP platform, for example, combines location, crop and growth-stage information with forecast weather conditions to generate crop-specific advisories. The system can operate down to Gram Panchayat-level locations and provides a five-day forecast for agriculturally relevant weather parameters.

**Seasonal forecasts**

Seasonal forecasts can help with broader decisions, including:

- crop selection;
- sowing windows;
- water-resource planning;
- choice of crop duration;
- contingency planning.

However, seasonal forecasts contain greater uncertainty than short-range forecasts. They are therefore better suited to risk management than to highly specific field operations.

**Soil Moisture: Understanding What Is Happening Now**

Weather tells us what may happen next. Soil moisture tells us what the field currently holds. This distinction is important. Two fields can receive the same rainfall but have very different moisture conditions because of differences in soil texture, drainage, organic matter, slope, previous irrigation and crop cover. A sandy soil may lose water rapidly, whereas a clay-rich soil may retain water for longer. A field with a high-water table may behave differently from an adjacent upland field. Consequently, rainfall alone cannot provide a complete picture of crop water availability.

Soil moisture can be measured through:

- in-situ soil-moisture sensors;
- capacitance or electromagnetic sensors;
- remote sensing;
- soil-water balance models;
- combinations of sensors, weather observations and crop models.

Recent research on soil-moisture forecasting highlights the growing use of historical soil moisture, weather and irrigation observations to predict future soil conditions. Such forecasting is increasingly being investigated for irrigation decision support. This creates an important possibility. Instead of asking whether the field is simply "wet" or "dry," a decision system can estimate whether the soil is likely to remain within an acceptable moisture range until the next expected rainfall event.

## Crop Phenology: The Missing Biological Dimension

Weather and soil moisture describe the environment. Phenology describes the crop's response and developmental stage. A rice plant at the vegetative stage does not have exactly the same water requirement or sensitivity to stress as a rice plant at flowering. Similarly, moisture stress around flowering or grain filling can have consequences that are quite different from stress during an earlier stage. Crop phenology includes stages such as:

- germination;
- emergence;
- seedling establishment;
- tillering;
- stem elongation;
- flowering;
- grain filling;

- physiological maturity.

The timing of these stages is influenced by temperature, day length, variety and environmental conditions. Climate change can alter phenological development. Warmer temperatures can accelerate crop development, potentially shortening the time available for biomass accumulation and changing the timing of sensitive stages. Recent literature notes that climate-driven changes in temperature and extreme events can modify crop phenology and productivity. Phenology can be estimated through field observations, crop models, accumulated temperature or degree-day approaches, and remote sensing indicators such as vegetation indices. This becomes particularly useful when combined with soil moisture.

For example:

**Dry soil + vegetative stage + low rainfall probability**
→ irrigation may be required.

**Dry soil + flowering stage + high temperature forecast**
→ irrigation may become a higher-priority intervention.

**Adequate soil moisture + grain filling + significant rainfall forecast**
→ irrigation can potentially be postponed.

**High soil moisture + heavy rainfall forecast + sensitive root system**
→ drainage may become more important than irrigation.

The same weather event can therefore lead to different recommendations depending on crop stage and soil condition.

## Bringing the Information Together

The real strength of the approach lies not in any single technology but in the integration of information.

A simple conceptual decision chain can be represented as:

**Weather Forecast → Soil-Water Balance → Crop Phenology → Risk Assessment → Agronomic Action**

The system first considers the expected weather. It then estimates how that weather will affect soil moisture. The crop's current developmental stage is introduced next. Finally, the system assesses the likely risk and recommends an action.

For irrigation, the logic can be expressed as:

**Current soil moisture + expected rainfall + expected evapotranspiration + crop growth stage = irrigation requirement**

The calculation does not have to be complicated from the farmer's perspective. A sophisticated model may operate behind the scenes, while the farmer receives a simple recommendation.

This principle is important because more information does not automatically mean better decision-making. A farmer does not need a dashboard filled with graphs if the final recommendation remains unclear.

## Applications in Climate-Smart Agronomic Management

### Irrigation Scheduling

Irrigation is perhaps the most obvious application.

Fixed irrigation intervals can result in both over-irrigation and under-irrigation. An integrated system can identify when irrigation is actually required by considering soil moisture, forecast rainfall and crop demand.

This can improve:

- water productivity;
- energy efficiency;
- crop resilience;
- irrigation timing;
- groundwater conservation.

The approach is particularly useful where irrigation water is limited.

A recent Indian climate-informed irrigation initiative illustrates this direction. The Climate-Informed Irrigation Decision Support System (CI-IDSS) developed for minor irrigation systems integrates crop modelling, climate information, remote sensing-derived phenology, soil datasets and optimization techniques for water allocation.

**Fertilizer Management**

Weather and soil moisture also influence fertilizer decisions.

Applying nitrogen immediately before intense rainfall can increase the risk of nutrient movement or loss. Applying fertilizer to a severely water-stressed crop may also be less effective because crop uptake is constrained.

An integrated system could therefore recommend fertilizer application only when:

- the crop is at an appropriate growth stage;
- soil moisture is adequate;
- substantial rainfall is not expected immediately;
- field conditions permit effective application.

Such recommendations can reduce unnecessary input losses and potentially improve nutrient-use efficiency.

**Pest and Disease Management**

Many pests and diseases are influenced by temperature, humidity, rainfall and crop growth stage.

The combination of phenology and weather forecasting can improve the timing of surveillance and preventive measures.

For instance, a disease risk model may become more useful when it knows that:

1. the crop has entered a susceptible growth stage;
2. humidity is expected to remain high;
3. rainfall is likely;
4. the crop canopy is already dense.

Instead of applying pesticides according to a fixed calendar, farmers can be encouraged to monitor fields more intensively during periods of elevated risk.

**Sowing and Crop Establishment**

Forecast information can support sowing decisions when combined with information about soil moisture.

A farmer may wait for adequate rainfall to establish a rainfed crop. But waiting too long can shorten the growing season. Conversely, sowing immediately after a small rainfall event may be risky if a long dry spell is expected afterward.

A phenology-based system can estimate whether the crop has sufficient time to complete important developmental stages before the end of the season.

This is particularly valuable under uncertain monsoon behaviour.

**Harvesting and Post-Harvest Management**

Weather forecasts can also assist harvest decisions.

If a mature crop is ready for harvesting and several days of rainfall are expected, harvesting slightly earlier may reduce field losses, provided grain moisture and crop maturity are acceptable.

Similarly, forecast information can help farmers plan:

- drying;
- transport;
- temporary storage;
- threshing;
- machinery availability.

Thus, climate-smart agronomy extends beyond crop production itself.

## Case Study: Climate-Informed Irrigation Management in Odisha

**Background**

Odisha provides an interesting setting for examining integrated climate-smart agricultural management. The state contains rainfed as well as irrigated farming systems, and rice is an important component of many agricultural landscapes. Farmers can face both water scarcity and excess rainfall, sometimes within the same agricultural season.

This creates a difficult management problem. The question is not simply whether water is available somewhere in the irrigation system. The more relevant questions are:

- When should water be supplied?
- Which fields need it most?
- What stage is the crop in?
- How much rainfall is expected?
- How much water is already present in the soil?
- What happens if irrigation is postponed?

A conventional irrigation schedule cannot answer all of these questions.

**The Darpanarayanpur Pilot**

A recent technical report on climate-smart water management describes the development and preliminary evaluation of a **Climate-Informed Irrigation Decision Support System (CI-IDSS)** for minor irrigation systems in India. The Darpanarayanpur Minor Irrigation Project in Odisha is being used as a representative pilot site. The system brings together several information streams rather than relying on a single source.

The reported framework integrates:

- crop modelling through APSIM;
- CMIP6 climate information;
- remote-sensing-derived crop phenology;
- soil datasets;
- optimization-based water allocation.

This is significant because it connects long-term climate information with seasonal planning and real-time agricultural management.

The basic idea is straightforward: water allocation should reflect both the environmental conditions and the biological requirements of the crop.

**How the Integrated System Can Work at Field Level**

Imagine a rice field within an irrigation command area.

The crop model indicates that the crop has entered a sensitive developmental phase. Remote sensing and field information help establish the phenological stage. Soil data indicate the water-holding characteristics of the field, while soil-moisture observations or estimates provide information about the current water status.

The weather forecast then indicates whether rainfall is likely over the next few days.

The system can combine these factors.

**Situation A: Moist soil and expected rainfall**

If soil moisture is adequate and rainfall is likely, irrigation can be postponed.

This saves water without exposing the crop to unnecessary stress.

**Situation B: Declining soil moisture and dry forecast**

If soil moisture is approaching a critical level and little rainfall is expected, irrigation can be prioritized.

**Situation C: Crop at a sensitive stage**

If the crop is flowering and the forecast suggests high temperature with little rainfall, the irrigation decision may become more urgent than it would be during an earlier growth stage.

**Situation D: Heavy rainfall expected**

If the soil is already saturated and heavy rainfall is forecast, the priority may shift from irrigation to drainage and field protection.

The value of the system therefore comes from **context**.

## A Practical Example of Decision-Making

Consider a hypothetical one-hectare rice field managed under limited irrigation.

The farmer normally irrigates every five days. Under conventional scheduling, the fifth day arrives and irrigation is applied.

Now consider an integrated approach.

**Day 1**
Soil moisture is adequate. The crop is in the vegetative stage.
**Day 2**
The weather forecast indicates moderate rainfall within 24–48 hours.
**Day 3**
Rainfall occurs.
**Day 4**
Soil moisture remains above the irrigation threshold.
**Day 5**
The traditional calendar says "irrigate," but the integrated system says "wait."

This is a small decision, but repeated across many fields and irrigation cycles, such decisions can produce meaningful water savings.

Now consider a second scenario.

The crop is approaching flowering. Soil moisture is declining, temperatures are high and the forecast shows several dry days ahead.

The same five-day calendar may again say "irrigate on Day 5." But the integrated system could identify the situation earlier and recommend irrigation before the crop reaches a critical stress level.

The difference is not simply technological. It is a change in the **timing and quality of the decision**.

## Evidence from Weather-Based Advisory Services in India

India already has experience with translating weather information into agricultural advice.

The India Meteorological Department's agrometeorological advisory system provides weather-based recommendations for agricultural operations. Research from climate-resilient agriculture initiatives has reported that farmers can use forecast-based advisories to reduce risks associated with abnormal weather. The development of KALP represents another step toward automated, location-specific agricultural decision support. It combines location, crop and crop stage with forecast conditions and generates impact-based advisories. This is an important lesson for integrated soil-moisture and phenology systems: the technological infrastructure for weather-based advisories already exists in India. The next step is to connect it more effectively with field-level soil and crop information.

## Why Soil Moisture and Forecasts Should Not Be Used Separately

There is a temptation to identify one "best" technology. In practice, this is rarely appropriate.

A weather forecast is uncertain. A sensor is local but represents only a particular point or sampling area. A crop model is useful for understanding processes but depends on assumptions and input quality. Remote sensing provides spatial coverage but may not directly measure root-zone moisture.

Each source has limitations.

Their combination can compensate for some of those weaknesses.

For example:

**Weather forecast:** "Rain is expected."
**Soil moisture:** "The field is already wet."
**Phenology:** "The crop is at flowering."

Together:

**Management recommendation:** "Do not irrigate now; monitor the field and reassess after the forecast rainfall."

This is much closer to the information farmers actually need.

Recent research on soil-moisture monitoring also points to the growing use of IoT, remote sensing, machine learning and other technologies, while identifying challenges such as sensor calibration, connectivity and cost.

## Role of Remote Sensing and Crop Models

Field sensors are valuable, but it is not realistic to place sensors in every field. This is where remote sensing can play a complementary role.

Satellite observations can provide information about:

- vegetation condition;
- crop development;
- canopy characteristics;
- spatial differences between fields;
- seasonal crop progression.

Phenology derived from remote sensing can help identify when different areas within an irrigation command reach important developmental stages.

Crop models can then simulate crop growth under different combinations of weather, soil and management.

The combination is particularly powerful:

**Satellite → What is happening spatially?**
**Sensor → What is happening locally?**
**Weather forecast → What may happen next?**
**Crop model → How might the crop respond?**
**Decision-support system → What action is preferable?**

This architecture can support both field-level and command-area-level management.

## The Role of Artificial Intelligence and Machine Learning

Artificial intelligence can strengthen the integration process, but it should not be treated as a replacement for agronomic knowledge.

Machine-learning models can help forecast soil moisture, identify crop stages from satellite imagery, estimate yield and detect patterns associated with crop stress. Recent research has explored models such as Random Forest, convolutional neural networks and long short-term memory networks for agricultural prediction and resource management.

For soil moisture, machine-learning models can use historical observations of:

- soil moisture;
- rainfall;
- temperature;
- evapotranspiration;
- irrigation;
- vegetation conditions.

The model can then estimate future moisture conditions.

However, the use of AI introduces new questions. What happens when sensors fail? What happens when a forecast is wrong? Can farmers understand why a recommendation was generated? Does a model trained in one soil type work in another?

For climate-smart agriculture, **explainability and reliability are as important as predictive accuracy**.

## Challenges in Implementing Integrated Systems

### Data Quality

A sophisticated system cannot compensate for consistently poor input data.

Incorrect soil characteristics, missing sensor observations or inaccurate crop-stage information can lead to poor recommendations.

Regular calibration and validation are therefore essential.

### Forecast Uncertainty

No weather forecast is perfectly accurate.

A rainfall forecast should therefore be interpreted probabilistically rather than as a guarantee.

Decision systems should be designed around risk rather than pretending that uncertainty does not exist.

**Cost**

Sensors, connectivity, remote-sensing services and computing infrastructure can be expensive for smallholders.

A climate-smart system must therefore be economically realistic.

A useful approach may be to combine a limited number of sensors with satellite observations and weather information rather than installing expensive equipment everywhere.

**Digital Connectivity**

Many rural areas experience intermittent internet or mobile connectivity.

Decision-support systems should therefore be capable of delivering recommendations through multiple channels, including mobile applications, SMS, local agricultural officers and farmer organizations.

**Farmer Trust**

Perhaps the most important challenge is trust.

If a system repeatedly gives recommendations that do not match field conditions, farmers will stop using it.

The farmer's own observation should not be discarded. Instead, technology should strengthen local knowledge.

A farmer who notices that a particular field dries faster than neighbouring fields has information that a generalized model may not capture.

The best system is therefore not one that tells the farmer, "The computer is right."

It is one that says, in effect, "Here is what the data suggest; now let us combine that with what you are seeing in your field."

## From Data to Action: A Farmer-Centred Framework

A successful climate-smart decision system should ultimately reduce complexity for the farmer.

A practical framework can follow five steps.

**Step 1: Observe**

Collect weather, soil-moisture and crop-stage information.

**Step 2: Predict**

Estimate rainfall, temperature, evapotranspiration and future soil moisture.

**Step 3: Interpret**

Determine how the expected conditions interact with the crop's current phenological stage.

**Step 4: Decide**

Compare possible actions, such as irrigating, waiting, draining, spraying, fertilizing or harvesting.

**Step 5: Learn**

Record what actually happened and use the information to improve future recommendations.

The final step is often overlooked.

A decision-support system should learn from the farm. If the predicted rainfall did not occur, the soil dried faster than expected or the crop stage was misidentified, the system should be adjusted.

Over time, the system becomes increasingly location-specific.

## Broader Implications for Climate-Smart Agriculture

The integration of weather, soil and phenology has implications beyond irrigation.

It can contribute to all three major dimensions of climate-smart agriculture.

**Productivity**

Better timing of water, nutrients and crop protection can help protect yields.

**Adaptation**

Farmers can respond more quickly to drought, heat, excessive rainfall and changing crop development.

**Mitigation**

More efficient use of water, fertilizer, fuel and electricity can reduce unnecessary resource consumption and associated emissions. However, the three objectives do not always align automatically. For example, maximizing production in one season may require additional inputs, while reducing emissions may require different management. Recent reviews emphasize that climate-smart agriculture involves trade-offs and must be adapted to local social, economic and environmental conditions. Therefore, integrated decision support should help farmers manage risks rather than promise a single universally optimal solution.

## Future Directions

The next generation of agricultural decision-support systems is likely to become more dynamic and localized. Instead of a farmer receiving a generic advisory for an entire district, systems may increasingly generate recommendations based on:

- field location;
- soil characteristics;
- crop variety;
- crop developmental stage;
- recent irrigation;
- current soil moisture;
- short-term weather forecast;
- seasonal climate outlook;
- satellite observations;
- farmer's available water;
- economic priorities.

This would move agriculture closer to **field-specific climate management**.

There is also considerable potential for integrating farmer-generated observations. Mobile applications could allow farmers to report crop stages, pest outbreaks, waterlogging or drought symptoms. These observations could complement sensor and satellite data.

Another important direction is uncertainty-aware decision-making. Rather than giving a single deterministic recommendation, systems could communicate risk in practical terms:

**Low risk:** irrigation can be postponed.

**Moderate risk:** monitor soil moisture and reassess tomorrow.

**High risk:** irrigation is recommended before the expected dry period.

Such communication may be more useful than complicated probability figures.

## Conclusion

Climate-smart agriculture does not necessarily require farmers to abandon traditional knowledge or replace it with sophisticated technology. The more realistic objective is to connect experience with better information. Weather forecasts tell us what may happen. Soil moisture tells us what is happening beneath the crop. Phenology tells us how important the conditions are for the plant at that particular moment. When these three sources are combined, agricultural management becomes more responsive to actual field conditions. The Odisha case illustrates the direction in which agricultural decision support is moving. The Climate-Informed Irrigation Decision Support System being developed around the Darpanarayanpur Minor Irrigation Project brings together crop modelling, climate information, remote-sensing-derived phenology, soil information and water-allocation optimization. At the advisory level, India's weather-based agricultural services are also moving toward more location- and crop-stage-specific recommendations. The central lesson is simple: **climate-smart management is not about predicting the weather perfectly; it is about making better decisions despite uncertainty.** A forecast may be wrong. A sensor may fail. A crop may develop faster than expected. Rainfall may arrive earlier or later than predicted. A robust management system must therefore continuously combine information, assess risk and adapt.

For farmers, the ultimate output should not be a complicated model or a collection of graphs. It should be a timely answer to a practical question:

**What should I do today, given my crop, my soil, my water and the weather that is likely to come?**

That is where the combination of weather forecasts, soil moisture and crop phenology can make climate-smart agriculture genuinely useful, not merely as a technological concept, but as a practical approach to managing farms under an increasingly uncertain climate.

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