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When Weather Changes the Economics of Agronomy: Climate-Responsive Optimization of Input Use in Field Crops

*Sharmistha Chhualsingh
Department of Agricultural Meteorology, College of Agriculture, OUAT, Bhubaneswar, Odisha, India
*Corresponding Author's email: scsingh2895@gmail.com

Agriculture has always been a business conducted under uncertainty. Farmers make decisions about seed, fertilizer, irrigation, pesticides and labour before they know exactly what the season will bring. A few decades ago, this uncertainty was often described simply as the "risk of farming." Today, however, weather variability is becoming more frequent, less predictable and more economically significant. A fertilizer application that is profitable in a normal rainfall year may produce very little return when a long dry spell follows. The same quantity of nitrogen can become highly valuable when rainfall and soil moisture are favourable, but wasteful when heavy rain immediately after application causes nutrient losses. An irrigation that saves a crop during a dry week may be unnecessary expenditure if substantial rainfall arrives the following day. Similarly, a pesticide applied according to a fixed calendar may become an avoidable cost if weather conditions do not favour the pest or disease. This changes an important principle of agronomy. The question is no longer simply "How much input should be applied?" It is increasingly "How much input should be applied, when should it be applied, and under what weather conditions will that input generate the best economic return?"

This is the foundation of climate-responsive agronomy. Climate-responsive input management does not mean abandoning fertilizers, irrigation, pesticides or improved seeds. Instead, it means using these inputs more intelligently by combining crop requirements with information about soil, weather, crop stage and expected economic returns. The objective is to produce more reliable yields with every unit of fertilizer, water, labour and money invested. The issue is particularly important in India, where agriculture remains highly exposed to monsoon variability. Government assessments under the National Innovations in Climate Resilient Agriculture (NICRA) have identified hundreds of agricultural districts as vulnerable to climate change. Modelling studies have also indicated substantial potential reductions in crop yields under future climate scenarios if adaptation measures are not adopted. The economics of agronomy, therefore, is gradually moving from a static model to a dynamic one. The farmer is not simply choosing an input package. The farmer is choosing a strategy for managing uncertainty.

The Changing Relationship Between Weather and Farm Economics

Traditional agronomic recommendations are usually expressed in relatively fixed terms: a particular crop requires a certain quantity of nitrogen, phosphorus and potassium; irrigation should be provided at specified intervals; pesticides should be applied when a particular pest reaches an economic threshold. These recommendations remain valuable. But weather can change the economic outcome of almost every recommendation. Consider nitrogen fertilizer. Nitrogen is essential for vegetative growth, tillering and yield formation in crops such as rice, wheat and maize. Yet nitrogen applied at the wrong time may be lost through volatilization, leaching, runoff or denitrification. Heavy rainfall immediately after application can reduce the amount available to the crop. On the other hand, withholding nitrogen during a favourable growth period can reduce yield potential. The economic consequence is straightforward. The farmer pays for the fertilizer whether or not the plant ultimately receives the nutrient. The same principle applies to irrigation. Water is not merely a physical input; it is an economic input involving pumping costs, electricity or diesel, labour and sometimes opportunity costs. When water availability becomes uncertain, the value of an irrigation event depends on the probability of rainfall, soil moisture, crop growth stage and expected yield loss. Weather therefore influences both **input productivity** and **input profitability**.

A useful way to express this relationship is:

Economic value of an input = Expected additional crop return – Cost of the input – Cost of climate-related loss

Under stable conditions, the first two components may dominate the calculation. Under variable weather, the third component becomes much more important.

This is why climate-responsive agronomy should be viewed not merely as an environmental approach but as an **economic management strategy**.

From Maximum Yield to Maximum Economic Efficiency

One of the most important changes in modern agronomy is the shift from maximizing yield to maximizing economic efficiency.

Maximum yield and maximum profit are not always the same.

For example, suppose an additional 30 kg of nitrogen increases the yield of a crop by 150 kg. If the value of that additional grain is lower than the cost of the fertilizer and its application, the farmer has increased yield but reduced profit.

The situation becomes even more complicated under uncertain weather.

In a good rainfall year, additional fertilizer may produce a strong yield response. In a drought year, the response may be weak because water, rather than nitrogen, becomes the limiting factor. Applying more fertilizer under drought conditions may therefore increase expenditure without producing a corresponding yield increase.

This leads to the concept of **marginal productivity of inputs**.

Farmers should ideally continue adding an input only while the value of the additional yield generated by that input is greater than its additional cost.

Climate changes this relationship because weather determines whether the crop can convert the input into harvestable biomass and grain.

The economic optimum therefore moves with the weather.

This is particularly important for nitrogen. Current Indian estimates indicate that nutrient-use efficiency can be relatively low, especially for nitrogen and phosphorus. Government data based on ICAR and other experimental studies place nitrogen-use efficiency broadly around 30–45 percent, phosphorus around 15–25 percent and potassium around 50–60 percent.

These figures should not be interpreted as meaning that most fertilizer is simply "wasted"; nutrient-use efficiency depends on crop, soil, management and measurement method. They do, however, demonstrate why improving the timing and placement of nutrients can have considerable economic value.

Weather as an Agronomic Input

Weather forecasts are often treated as information external to farming. In climate-responsive agronomy, weather information becomes part of the production system itself.

A short-term rainfall forecast can influence whether fertilizer is applied today or postponed.

A forecast of several dry days can influence irrigation scheduling.

A period of high humidity and prolonged leaf wetness can influence disease-management decisions.

A heatwave warning can change irrigation priorities during sensitive reproductive stages.

A delayed monsoon can affect crop choice, sowing date and even the decision to shift from a long-duration variety to a shorter-duration crop.

In other words, weather information can be converted into **economic information**.

The value of a forecast is highest when it changes a decision that has a measurable financial consequence.

For example:

- If rain is expected within the next 24 hours, nitrogen application may be postponed where heavy rainfall would cause losses.
- If a dry spell is forecast during a crop's sensitive stage, irrigation can be prioritized for fields with the greatest yield-risk exposure.
- If conditions are unsuitable for a fungal disease, unnecessary preventive spraying can sometimes be avoided.
- If extreme rainfall is expected close to harvest, harvesting and drying operations may be brought forward where feasible.
- If a delayed monsoon makes establishment of a long-duration crop risky, farmers can shift to shorter-duration or stress-tolerant alternatives.

The objective is not to predict the weather perfectly. Forecasts will always contain uncertainty. The objective is to use available information to make **better decisions than would be possible without it**.

India's agricultural extension system is increasingly moving in this direction. ICAR agro-advisories emphasize the importance of location-specific weather information for sowing, crop management, pest and disease control, harvesting and other decisions.

Climate-Responsive Optimization of Major Farm Inputs

Fertilizer: From Fixed Doses to Flexible Nitrogen Management

Fertilizer is one of the clearest examples of why weather-responsive agronomy matters.

Nitrogen should ideally be available when the crop needs it. Applying the entire quantity at once is often less efficient than dividing it into appropriate doses. Split application, soil testing, crop sensing and improved placement can all help synchronize nitrogen supply with crop demand.

The FAO Climate-Smart Agriculture Sourcebook identifies improved fertilizer efficiency as an important component of climate-smart agriculture and highlights practices such as split nutrient application, precision placement and deep placement of urea in rice.

Weather information can improve this approach further.

Suppose a rice farmer is planning a nitrogen top dressing. If a heavy rainfall event is expected shortly after application, postponing the application until the field and forecast conditions are more favourable may improve nutrient recovery. Conversely, if the crop is approaching a high-demand stage and weather conditions are favourable, timely application can prevent nutrient deficiency.

This does not mean following a forecast blindly. Soil moisture, crop colour, crop stage, soil type and field drainage must also be considered.

The best system combines:

Soil information + crop demand + weather forecast + farmer experience + economics.

This is more sophisticated than simply reducing fertilizer rates.

Irrigation: Water at the Right Time, Not Water at Any Time

Water is another input whose value changes rapidly with weather.

In water-limited agriculture, the economic question is not simply whether the crop needs water. It is which field needs water first and at what stage.

A farmer with limited irrigation water may have several fields but insufficient water to irrigate all of them. Applying equal amounts everywhere may be less profitable than prioritizing crops at sensitive growth stages.

For rice, for instance, irrigation management can be linked with crop establishment method, soil type, rainfall and crop stage. In wheat, irrigation decisions can be closely linked to critical stages of crop development and the probability of rainfall.

Technologies such as tensiometers, soil-moisture sensors and weather-based irrigation scheduling can help farmers avoid unnecessary irrigation.

This is especially relevant in Odisha. The state's agricultural strategy has increasingly emphasized efficient water use, soil moisture management and climate resilience. A recent Odisha government assessment specifically identifies water efficiency and technologies such as soil-moisture sensors and automated irrigation as opportunities for improving farm economics.

Water-saving practices can therefore have a double benefit: reducing resource consumption while protecting the farmer from unnecessary expenditure.

Pesticides: Weather Can Change the Need for a Spray

Pesticide decisions are often made using calendar schedules: spray at a particular crop age, then repeat after a certain interval.

Climate-responsive pest management takes a different approach.

Pest populations are strongly influenced by temperature, humidity, rainfall, crop canopy and surrounding vegetation. Disease development can also depend on combinations of temperature and moisture.

Therefore, weather information can be combined with field scouting to estimate whether an intervention is economically justified.

The principle is simple:

Do not spray because the calendar says it is time to spray. Spray because the crop, pest and weather conditions indicate that the expected benefit is greater than the cost and risk of spraying.

This approach is consistent with integrated pest management, in which economic thresholds, biological control, resistant varieties and cultural practices are considered alongside pesticides.

For farmers, this can mean lower chemical expenditure, fewer unnecessary applications and reduced risk of pesticide resistance.

Seed Choice Is Also an Economic Decision Under Climate Risk

Climate-responsive input optimization begins even before the first fertilizer bag reaches the field. The choice of variety is one of the most important risk-management decisions a farmer makes. A high-yielding variety under ideal conditions may not necessarily be the most profitable variety under uncertain rainfall. A slightly lower-yielding variety with drought, flood, salinity or heat tolerance may produce a more stable return over several years. This distinction between **maximum potential yield** and **yield stability** is increasingly important. Odisha provides a good illustration because rice production occurs across rainfed, irrigated, lowland, drought-prone and coastal environments. ICAR has long recommended location-specific rice varieties and management practices for conditions such as submergence, drought, iron toxicity and coastal salinity. More recently, KVK-Khordha demonstrated climate-resilient rice varieties including Pooja, Kalachampa and Swarna Sub-1 in flood-prone areas as part of climate-resilience measures. The economic logic is important.

A farmer may prefer a variety that produces 4.5 tonnes per hectare reliably over one that can produce 5.5 tonnes in a good year but falls to 2.5 tonnes during a climatic shock.

In risky environments, **stability itself has economic value**.

Case Study: Climate-Responsive Rice Production in Odisha

Why Odisha Makes a Useful Case

Odisha is an appropriate setting for examining climate-responsive agronomy because rice dominates much of the state's agricultural landscape, while farmers experience a mixture of drought, excess rainfall, flooding, delayed monsoon, dry spells and uneven water availability.

The challenge is particularly serious for smallholders. An Odisha government document reports an average landholding of about 0.95 hectare and indicates that approximately 93 percent of farmers are small and marginal. For such farmers, input inefficiency is not a minor technical issue. A wasted bag of fertilizer, unnecessary irrigation or failed pesticide application can directly affect household income. The state has also developed systems for crop-weather monitoring and contingency planning. Its Kharif campaign describes the use of rainfall, monsoon status, dry-spell information, crop coverage, input availability, reservoir conditions and agro-advisories to support crop-weather decisions. This provides a useful real-world context for understanding how weather can influence input economics.

The Farmer's Traditional Problem

Consider a representative small rice farmer in a rainfed or partially irrigated area of Odisha.

The farmer has a limited budget and typically purchases seed, fertilizer, herbicides and pesticides at the beginning of the season. Under a conventional approach, the farmer may follow a standard fertilizer recommendation and apply irrigation whenever water is available.

The difficulty begins when the monsoon behaves differently from expectation.

If rainfall is delayed, transplanting may be postponed.

If rainfall comes in a short period followed by a dry spell, nitrogen uptake may be affected.

If excessive rain occurs after fertilizer application, nutrient losses can increase.

If water remains stagnant, some fields may suffer while others benefit.

If the monsoon withdraws early, the possibility of establishing a second crop becomes uncertain.

Thus, the farmer's input package is interacting continuously with the weather.

A Climate-Responsive Alternative

A more responsive system would begin with a simple field-level assessment.

The farmer or extension worker would consider:

1. Expected rainfall over the coming week.
2. Soil moisture status.
3. Crop growth stage.
4. Variety and its stress tolerance.
5. Field drainage and water-holding capacity.
6. Current crop nutrient status.
7. Pest and disease observations.
8. Available irrigation water.
9. Input prices and expected crop value.

Suppose the rice crop is approaching an important nitrogen-demand stage, but heavy rainfall is forecast.

Instead of immediately broadcasting fertilizer, the farmer may wait for a more suitable application window, provided the crop can safely tolerate the delay.

If the forecast instead indicates a short dry spell, the farmer may prioritize irrigation for fields where the crop is at a sensitive stage.

If flood risk increases, the farmer may prioritize drainage and protect vulnerable fields rather than investing additional fertilizer in a crop already under severe stress.

This is a fundamental change in thinking.

The farmer is no longer asking:

"What does the fertilizer recommendation say?"

The farmer is asking:

"What does the crop need, what can the weather support, and where will my next rupee produce the greatest return?"

Evidence from Khordha: Location-Specific Technologies

A particularly relevant example comes from Khordha district, Odisha, where ICAR's Indian Institute of Water Management implemented the Farmer FIRST Programme in the villages of Haridamada, Jamujhari and Barapita.

The area has a tropical monsoon climate, approximately 1,100–1,200 mm of annual rainfall, variable soil conditions and uneven water availability. The programme targeted a predominantly smallholder and tribal farming community.

Certified high-yielding rice varieties were introduced along with scientific practices including line transplanting and biofertilizer-based seed treatment. The interventions reportedly produced yield gains of about 10–20 percent and improved benefit-cost ratios and water productivity.

The significance of this case goes beyond the individual technologies.
The programme did not depend on a single "magic" input. It combined seed, crop establishment, nutrient management, water management and location-specific decision-making.
That is precisely what climate-responsive agronomy requires.
A farmer facing variable rainfall cannot solve every problem with additional fertilizer. The solution is usually a package in which each input supports the others.

A Second Lesson from Odisha: Green Manuring and Drought Risk

Another useful example comes from Raruan block of Mayurbhanj district.
Under the Odisha Agriculture Drought Mitigation Programme, ICAR-CRIDA and local agencies have promoted dhaincha-based green manuring. In 2026, seed was distributed to 97 farmers covering approximately 140 acres across several villages. The intervention was designed to improve soil fertility, build soil organic carbon and reduce dependence on inorganic fertilizers.
At first glance, green manuring may appear to be a purely soil-health intervention. Economically, however, it can be understood as a form of **input substitution and risk management**.
Organic matter can improve soil structure and water-holding characteristics. Biological nitrogen fixation can contribute nitrogen to the farming system. Better soil condition may help the crop cope with periods of moisture stress.
The benefit is therefore not necessarily visible as a single yield increase in one season. Part of the value comes through reduced dependence on purchased inputs and improved resilience over time.
This is an important point for climate-responsive economics: **not every benefit has to appear as immediate yield.**

What the Case Study Tells Us About Optimization

The Odisha examples demonstrate three important principles.
First, the cheapest input is not always the most economical input.
A farmer may spend less by avoiding improved seed, soil testing or moisture management, but the resulting yield instability can make the total production system more expensive.
Second, reducing inputs is not the same as optimizing inputs.
Climate-responsive agriculture does not promote blanket fertilizer reduction. If nitrogen is deficient, applying less nitrogen can reduce yield and income.
The objective is to apply the **right quantity at the right time and place**.
Third, resilience has an economic value.
A production system that produces slightly less in a perfect year but performs much better during drought or flood may provide a higher average income over several years.
This suggests that farmers and policymakers should evaluate technologies using indicators such as:

- Net return per hectare
- Return per rupee invested
- Yield stability
- Water productivity
- Nutrient-use efficiency
- Labour productivity
- Risk of crop failure
- Cost of adaptation
- Long-term soil health

A technology that performs well on only one of these indicators may not be the best choice for smallholder agriculture.

The Role of Digital Agriculture and Weather Advisories

Climate-responsive agronomy is becoming increasingly dependent on information.

Automatic weather stations, satellite imagery, soil sensors, crop monitoring, mobile advisories and digital extension platforms can potentially turn weather data into field-level decisions.

Odisha's agricultural system already uses weather monitoring and advisories as part of crop contingency planning. The state has also established systems for disseminating advisories based on IMD forecasts and crop-weather conditions.

At the national level, ICAR has emphasized weather-based agro-advisories, while the Bharat-VISTAAR initiative launched in 2026 aims to combine agricultural information, weather-based advice, market information and farming practices through digital technology and multilingual delivery.

However, technology should not be confused with progress automatically.

A forecast has value only if a farmer can act on it.

If a farmer receives a rainfall alert but cannot delay fertilizer application because of labour constraints, the information may have limited practical value.

If a soil-moisture sensor recommends irrigation but electricity is unavailable, the recommendation cannot be implemented.

Therefore, digital agriculture should be designed around **decisions and constraints**, not simply around data.

The Economics of "Doing Nothing"

An often-overlooked aspect of climate-responsive agriculture is that sometimes the best decision is to **wait**.

Agriculture tends to reward activity. Farmers are often encouraged to sow, fertilize, irrigate and spray. But under uncertain weather, unnecessary action can itself become a cost.

Imagine a farmer who plans to irrigate tomorrow. A reliable forecast indicates substantial rainfall within 24 hours. If the crop is not under severe moisture stress, waiting may save the cost of pumping.

Similarly, postponing fertilizer application by two days may avoid nutrient loss from heavy rainfall.

Delaying a pesticide application until field scouting confirms a pest threshold may save the entire spraying cost.

This is sometimes called the **option value of waiting**.

Weather forecasts create an opportunity to delay an irreversible or costly decision until more information becomes available.

For small farmers, this can be particularly valuable because financial resources are limited.

Constraints to Climate-Responsive Input Management

Despite its potential, climate-responsive agronomy faces several barriers.

Forecast Uncertainty

Weather forecasts are not perfect. Farmers may hesitate to change established practices based on uncertain predictions.

The solution is not to promise perfect forecasts but to communicate uncertainty in practical terms.

Instead of simply saying "rain expected," advisories should explain the likely consequence:

"Heavy rain is likely in the next 24–48 hours; postpone urea application where possible."

That is more useful than raw weather information.

Small and Fragmented Holdings

A farmer managing one hectare across several small plots cannot always implement sophisticated recommendations separately on each field.

Climate-responsive agriculture therefore needs simple decision rules that can be adapted to smallholder conditions.

Input and Credit Constraints
Farmers sometimes apply fertilizer early because they have purchased it on credit. Even if weather information suggests postponement, financial arrangements may limit flexibility.
Input optimization must therefore consider the farmer's cash flow, not just crop physiology.
Weak Last-Mile Extension
Scientific recommendations are useful only when they reach farmers in understandable language.
The recent experience in Odisha, where weather-based agro-advisories are being strengthened through SMS, WhatsApp and other extension mechanisms, shows the importance of the last mile.

A Practical Framework for Climate-Responsive Agronomy
A practical framework can be built around five questions.
Question 1: What does the crop need?
Assess crop stage, nutrient status, soil moisture and potential yield.
Question 2: What is the weather likely to do?
Look at short-term forecasts, rainfall probability, temperature and extreme-weather warnings.
Question 3: What is the field capable of supporting?
Consider soil type, drainage, irrigation availability and previous crop conditions.
Question 4: What will the input cost?
Include fertilizer or chemical cost, labour, machinery, water, energy and opportunity cost.
Question 5: What is the expected economic return?
Estimate the likely yield benefit and compare it with the additional cost and risk.
This framework can be summarized as:
Crop requirement → Weather outlook → Field condition → Input cost → Expected return → Decision
The process should be repeated throughout the season rather than treated as a one-time planning exercise.

Implications for Agronomists and Extension Professionals
The role of the agronomist is also changing.
The agronomist of the future cannot work only with average yield data. Recommendations need to account for variability.
Instead of providing one fertilizer recommendation for an entire region, agronomists may increasingly provide decision ranges:
- If rainfall is normal, follow Plan A.
- If rainfall is delayed, follow Plan B.
- If a prolonged dry spell occurs, follow Plan C.
- If excessive rainfall is forecast, modify fertilizer and drainage operations.

This approach is closer to the way farmers actually experience agriculture.
It also encourages the development of **contingency-based agronomy**.
India has already developed District Agriculture Contingency Plans for agricultural districts to address weather aberrations and identify suitable climate-resilient crops and practices.
The next step is to make these plans more operational at farm level.

Policy Implications
Climate-responsive input management should not be left entirely to individual farmers.
Public policy has an important role in creating the conditions in which better decisions are possible.
Four areas deserve particular attention.
Weather information
Forecasts should be localized, timely and delivered through channels farmers actually use.
Soil and crop diagnostics

Affordable soil testing, crop sensors and extension support can help farmers move away from blanket input recommendations.

Incentives

Support programmes should increasingly reward efficient use of water, nutrients and other resources rather than simply increasing input consumption.

Farmer institutions

Farmer Producer Organizations, cooperatives and self-help groups can help smallholders access weather information, machinery, soil testing, irrigation technologies and improved inputs at lower individual cost.

The Odisha government's current programmes illustrate this broader movement toward sustainable and climate-resilient farming. Its organic farming programme, for example, explicitly links nutrient recycling and reduced dependence on external inputs with climate adaptation and improved farm income.

The Larger Economic Argument

The discussion about climate change in agriculture often focuses on declining yields, crop failures and environmental damage.

Those concerns are real, but another issue deserves equal attention: **the changing economics of every agronomic decision**.

Climate change does not simply reduce production. It changes the probability that an input will generate its expected return.

A kilogram of nitrogen has a different economic value under drought than under adequate moisture.

A litre of irrigation water has a different value before rainfall than after rainfall.

A pesticide application has a different value under favourable disease conditions than under dry weather.

A seed variety has a different economic value when the probability of flood or drought is high.

In this sense, weather acts almost like a variable price in the farm production function.

The physical input may remain the same, but its economic return changes.

That is why climate-responsive agronomy should not be considered a niche area of climate science. It is becoming a central component of farm management.

Conclusion

The future of field-crop agronomy will not be defined simply by producing more with more inputs. It will increasingly depend on producing reliably with **better-timed, better-targeted and economically justified inputs**.

Weather variability makes this shift unavoidable.

The farmer of the future will still use fertilizer, irrigation, improved seed and crop protection products. What will change is the decision process surrounding those inputs. Fertilizer will be applied according to crop demand and field conditions. Irrigation will be prioritized according to soil moisture and weather outlook. Pesticides will be used when pest and disease risk justifies the expenditure. Varieties will be selected not only for maximum yield but also for their ability to withstand climatic stress.

The experience of Odisha illustrates why this approach matters. Rice farmers working under uncertain rainfall and water availability cannot depend on fixed input packages alone. Location-specific technologies, climate-resilient varieties, green manuring, improved nutrient management, water-saving practices and weather-based advisories can work together to improve both productivity and economic resilience. Recent interventions in Khordha and Mayurbhanj demonstrate that climate adaptation can be linked directly with input efficiency and farmer livelihoods.

Ultimately, climate-responsive agronomy is about making agriculture more intelligent rather than simply more intensive.

The central question for agronomists and farmers is no longer:

"How much fertilizer, water or pesticide does this crop require?"
It is:
"Given the crop, soil, weather, market and available resources, what is the smallest and smartest investment that can produce a reliable return?"
That is where agronomy meets economics.
And as weather becomes more uncertain, that intersection will become increasingly important for the future of field-crop agriculture.

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