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Phenology-Based Agro-Meteorological Decision Support for Rice-Based Cropping Systems: Integrating Thermal Indices, Water and Nutrient Management for Climate Resilience

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Rice (*Oryza sativa* L.) is a staple food crop and a major component of agricultural systems in South and Southeast Asia. In India, the rice production is greatly affected by monsoon behaviour, temperature, rainfall distribution, solar radiation and availability of irrigation. Rice is important not only as a crop but also because it is usually followed by wheat, pulses, oilseeds and other crops. Thus weather conditions that influence rice growth may also influence the establishment and productivity of the succeeding crop. The Government of India estimates that national foodgrain production touched about 357.73 million tons in agricultural year 2024-25, demonstrating the continued importance of cereal production to the country's food security . More variability in the weather has made crop management more difficult. Delayed rainfall, prolonged dry spells, intense rainfall and flooding and episodes of high temperature may be experienced during the same growing season. Rice reproductive development is particularly sensitive to temperature stress. High temperature around flowering can interfere with anther dehiscence, pollen viability, pollination and fertilization leading to increased spikelet sterility . Heat during grain filling can also reduce grain weight and shorten the grain filling period. One major weakness of traditional farm advisories is their dependence on a fixed calendar schedule. Crop development, however, is not solely a matter of the calendar. It responds to genotype, temperature, photoperiod, radiation, soil moisture and crop management. Thus, rice crops established at different times may reach tillering, panicle initiation, flowering and maturity on different dates. Thus it is more reliable to associate management decisions with the crop's actual physiological stage. This is the basis of a phenology-based agro-meteorological decision support system. Such a system couples crop phenology with observed weather, weather forecasts, thermal indices, soil moisture and plant nutrient status to produce crop-stage specific recommendations. The basic rule is simple: the same weather event may require different management responses depending on the crop's growth stage.

Phenology and Thermal-Time-Based Crop Monitoring

Crop phenology is the study of the occurrence and timing of important developmental stages such as emergence, tillering, panicle initiation, booting, heading, flowering, grain filling and physiological maturity. Temperature is one of the primary environmental factors controlling the rate of these stages. The concept of thermal time is based on a progress of the crops when temperature is accumulated over a minimum threshold. The most commonly used thermal index is the Growing Degree Day (GDD): $GDD = (T_{max} + T_{min})/2 - T_{base}$; where T_{max} and T_{min} are daily maximum and minimum temperatures and T_{base} is the crop-specific base temperature. Daily values are usually set at zero if the result is less than zero and cumulative GDD is calculated by summing the daily thermal units from a chosen starting point. Other indices can provide additional information:

Heliothermal Unit (HTU) = GDD × bright sunshine duration
Photothermal Unit (PTU) = GDD × day length
Heat Use Efficiency (HUE) = economic yield / accumulated GDD
Phenothermal Index (PTI) = thermal units accumulated per unit duration of a phenophase.

These indices are useful for comparing varieties, environments and sowing dates and for improving predictions of crop development . But thermal requirements are not universal constants. Genotype, planting date, location and weather conditions during the season can alter the amount of thermal energy required to reach a specific developmental stage. Thus, thermal indices are most useful when continuously updated with observed weather and verified against field observations. This is a particularly important distinction for an operational decision-support system. The system should predict when the crop will likely flower based on accumulated thermal units and the current crop development, rather than predicting flowering on a certain fixed calendar date. The forecast can then be combined with the predicted weather for the next few days to identify potential risks.

Why Phenology-Based Management is Important Under Climate Variability

The main benefit of using phenology-based management is that it takes weather details and turns them into advice that is specific to the crop and its stage of growth. For instance some rain can be good when the crop is just starting. Too much rain near the end can cause problems like waterlogging or making it hard to harvest. Also high temperatures during the growing phase can have an effect than the same temperatures during the flowering phase. Heat stress is especially bad for rice when it is reproducing because high temperatures can stop pollen from being released and can make the pollen not work properly which leads to sterile flowers. An effective agro-meteorological advisory system should consider several interrelated factors, including the current phenological stage of the crop and the stage expected to be reached during the subsequent 5–15 days. It should also incorporate weather forecasts, particularly the likelihood and distribution of rainfall, along with the prevailing soil-moisture status and availability of irrigation water. In addition, the nutritional status of the crop should be assessed to determine its nutrient requirements. Potential weather-related risks should then be evaluated in relation to the crop stage and prevailing field conditions. Based on the combined assessment of these factors, an appropriate and timely crop-management recommendation can be developed. The value of this system is that it does not just tell farmers that there will be a heatwave or heavy rain. It explains what the event could mean for the crop at that time and what actions should be taken.

Parts of a Phenology-Based Agro-Meteorological Decision-Support System

Weather information

The system should use data collected from weather stations along with weather forecasts and predictions. The key weather parameters should include minimum temperature, rainfall, relative humidity, sunshine duration or solar radiation, wind speed, and cloud cover. Where available, the system should also incorporate soil temperature and soil moisture data. These data can be obtained from conventional weather stations, automated weather stations, satellites, and numerical weather prediction models. In India, existing weather-based agro-advisory systems already use similar meteorological information to provide recommendations to farmers, providing a strong foundation for developing such a system.

Crop phenology and thermal indices

Daily temperature data can be used to calculate GDD and other temperature-related indicators. Then these numbers are compared with values that are specific to a certain crop type and location. The process starts by collecting temperature data, which helps estimate how heat the crop has had and how far along it is in its growth. Then the expected weather is checked against the crops stage to find any problems like heat stress, not enough water or too much rain. Based on that good advice for managing the crop can be made. This method lets the growth of the crop and the way it is managed be watched and changed as the weather changes of just using a fixed calendar.

Soil moisture and water conditions

Managing water should look at rain expected rain, the moisture in the soil how much water is available for irrigation and the stage of the crop together. This is very important because much water or not enough can lower how much the crop produces. One of the ways to save water when growing rice is to use alternate wetting and drying. A study that looked at 56 studies and 528 comparisons found that using a version of this method cut water use by about 23.4% without causing big drops in yield.. Using a more extreme version caused big drops in yield which shows that the soil should not be too dry. A recent study with 437 sources found that using this method cut the amount of water used for irrigation by about 33.9% and made water use better while the drop in yield was only about 1.6%. These results back up using this method. They also show that irrigation should not be done on a strict schedule. The point where the soil starts to dry should match the soil the crop stage and the weather that is expected.

Crop nutrient levels

Nitrogen management is another part. Much nitrogen costs more and can cause pollution while not enough nitrogen stops the crop from growing well and affects the way it flowers and makes seeds. A nitrogen strategy based on phenology should look at the stage the crop's in and the nitrogen level in the plant along with the nutrients in the soil and the weather that is happening and coming. Combining all these things helps make advice for using nitrogen that fits the crops needs and the environment. Tools like leaf color charts, meters that measure chlorophyll sensors that look at the crop and ways to manage nutrients in places can help tell if adding more nitrogen is needed. Also applying nitrogen should not be done before heavy rain because there is a big chance of losing the nitrogen. So using nitrogen when the crop is at the stage and, with the help of weather forecasts can help use nitrogen better.

Decision rules and advisory generation

The final result should not just be a list of numbers. Instead the result should be a tip that a farmer can actually use. For example: Rice is approaching panicle initiation and moderate rainfall is expected during the five days. If soil moisture is adequate irrigation may be postponed. Nitrogen application should be scheduled after field conditions improve and crop nutrient status is assessed. These kinds of messages are much better than a weather forecast because these messages combine the crop stage the weather forecast, the field status and the management action.

Phenology-Based Water Management

Water management is the important part of growing rice that can survive climate change. Keeping the fields flooded all the time can keep the soil moisture good. This method often needs a lot more irrigation. AWD gives farmers a chance to use water while still growing plenty of rice if they use the right drying levels. The work done by Carrijo et al. (2017) Is very helpful here. Their look at 56 studies showed that mild AWD cut water use by 23.4%. However letting the field get too dry could drop the rice yield by 22.6% when compared to flooding. This shows that water-saving irrigation needs to change based on the rice growth stage than just using a machine. During the stages the rice needs plenty of moisture. During the development stage you might be able to let the soil dry out a little if the soil and weather allow it.. When the rice is near flowering you must avoid letting the rice get too dry because rice is very sensitive to stress, during reproductive development.

A phenology-based irrigation strategy may therefore follow the broad principle:

Crop stage	Major concern	General management approach
Establishment	Dry spell	Maintain adequate soil moisture
Tillering	Excess water/dry spell	Avoid unnecessary continuous flooding
Panicle initiation	Moisture deficit	Maintain adequate moisture
Flowering	Heat + moisture stress	Give priority to water availability

Crop stage	Major concern	General management approach
Grain filling	Moderate drying	Controlled irrigation according to soil status
Maturity	Heavy rainfall	Drain excess water and facilitate harvest
Pre-harvest	Excess moisture	Stop irrigation at appropriate maturity

The exact thresholds should be adjusted according to soil type, variety, local climate and irrigation conditions.

Phenology-Based Nutrient Management

Nitrogen is closely linked to tiller production, canopy growth, photosynthesis and yield formation in rice.. The efficiency of applied nitrogen depends strongly on when and how much nitrogen is added. A plant growth-stage strategy can split nitrogen management into three periods. Basal application: The basal dose should take into account soil fertility, expected yield the crop grown before residue handling and local nutrient-management guidelines. Tillering: Nitrogen demand rises as canopy growth and tiller production speed up. A split application can therefore tie nitrogen to crop condition and plant nitrogen status of a fixed number of days after transplanting. Panicle initiation: This is a shift from vegetative growth to reproductive growth. Adequate nitrogen availability supports tillers and panicle development. Application should follow crop need. Should preferably avoid periods right before heavy rainfall. This method makes nitrogen management more responsive.

Application to Rice-Based Cropping Systems

The proposed framework becomes especially useful when rice is seen as the element of a cropping sequence rather than as a stand-alone crop. In a rice–wheat system delayed rice maturity caused by rain or other weather stress can cut the window available for wheat start-up. Early prediction of rice maturity can therefore help farmers plan harvest time and the next land preparation. In a rice–pulse system timely rice harvest can free up remaining soil moisture for crops such as greengram, blackgram or lentil. Weather data can aid in picking a sowing window. In a rice–oilseed system delayed rice harvest can push mustard or other oilseed crops into favorable temperature and moisture conditions. Plant growth-stage prediction can therefore help in selecting succeeding crops and sowing windows. Similarly in a rice–rice system the length of the rice crop directly shapes the nursery and transplanting schedule of the next crop. Thus plant growth-stage management can shift focus from crop care to whole cropping-system management.

Proposed Decision-Support Framework

A practical decision-support system can integrate weather observations, short-term weather forecasts, crop growth indices and field-level information to generate timely recommendations. The system would first collect current weather observations and combine them with a 5–10 day weather forecast. Using these data, indices such as Growing Degree Days (GDD), Heliothermal Units (HTU) and Photothermal Units (PTU) can be calculated to estimate the progress of crop development and predict the occurrence of upcoming growth stages. The predicted crop stage can then be evaluated together with soil moisture conditions, expected rainfall and crop nutrient status. This assessment would help identify potential weather-related risks and determine appropriate management actions. Based on these conditions, the system can apply crop-stage-specific decision rules and generate a simple, practical and timely advisory for farmers. Modern technologies can further strengthen this framework. Automatic weather stations can provide real-time meteorological observations, while IoT-based soil-moisture sensors can improve irrigation scheduling. Remote sensingcan provide information on crop establishment, canopy development, biomass accumulation and water stress. Crop simulation models such as ORYZA, DSSAT and APSIM can also be incorporated to simulate crop development and evaluate alternative management strategies. However, technology should remain a means rather than an objective. The final advisory should be simple, locally relevant, scientifically sound and practical enough for farmers and extension workers to implement. Modern tools can strengthen the framework further. Automatic weather stations can give real-time data while IoT-based soil-moisture sensors can improve irrigation decisions. Remote sensing can supply information on crop start, canopy growth, biomass and water stress. Crop models such as ORYZA, DSSAT and APSIM can also be used to simulate crop progress and test management plans. However technology must stay a means, not a goal. The final recommendation must be clear locally relevant and doable for farmers and extension workers.

Conclusion

Plant growth-stage agro-meteorological decision support is a way to boost the resilience of rice-based cropping systems in the face of rising weather uncertainty. The main strength of this approach is its ability to link crop stage with weather risk and management action. Heat indices such as GDD, HTU and PTU can help monitor and forecast crop progress. They must be tuned to specific variety, location and season rather than used as fixed universal numbers. Likewise water and nitrogen management should change dynamically based on crop stage, soil condition and weather outlook. Studies show that managed AWD can cut irrigation needs a lot. Mild AWD reduces water use by 23% in one major synthesis and a wider global review shows reductions of around 34%. At the time harsh drying can lower yield underscoring the need for stage-specific and soil-specific management. The proposed framework therefore goes beyond date-based advice toward a system that is more dynamic, crop-responsive and climate-aware. Bringing together weather data, forecasts, heat indices, crop growth stages, soil moisture, nutrient status, remote sensing and crop modelling can improve the timing of irrigation, nitrogen application, drainage, pest and disease control and harvest. This integration is especially valuable in rice-based systems because decisions made during the rice crop set the stage for the following crops. Overall the future of advisory services should not be only about giving more weather data. The real chance lies in turning weather data into stage-specific actions that farmers can carry out at the moment. Plant growth-stage decision support offers a scientific path, to that goal and can help achieve better resource use, higher yield and stronger climate resilience in rice-based farming.

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