Irrigation Timing Tolerance in Staple Crops: Implications for Food Security under Climate Variability

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ABSTRACT

This paper reports on a forty-year field study — one of the longest of its kind — examining how three of the world's most important food crops respond to changes in irrigation timing. Working across smallholder farms in West Bengal, India, between 1985 and 2025, we tracked 327 individual plants of paddy rice, wheat, and potato through hundreds of growing seasons. What we found was, in some ways, exactly what experienced farmers have long suspected: crops appear to care not only about how much water they receive, but about when.

After two to three weeks on a consistent watering schedule, plants seemed to anticipate their irrigation — showing physiological signs of preparation before water even arrived. When we disrupted those schedules abruptly, yields fell by 15 to 35 percent, even when the total amount of water delivered remained exactly the same. Gentle, gradual schedule transitions, by contrast, produced almost no disruption at all.

We want to be straightforward about what this study is and is not. It is a careful, long-term observational record — not a controlled laboratory experiment. We cannot prove that irrigation timing alone caused the yield losses we observed, and we explicitly acknowledge that uncontrolled factors (weather, soil variation, observer effects) may have contributed. What we can offer is forty years of consistent, detailed documentation that a pattern exists — one consistent enough, and surprising enough, to deserve rigorous scientific investigation.

If future controlled experiments confirm what we observed, the food security implications are real. As climate change makes it increasingly difficult for farmers to maintain reliable watering schedules, the question of timing consistency — not just water volume — may become a meaningful factor in crop productivity that current agronomic science has simply never measured.

Keywords: irrigation timing, staple crops, paddy rice, wheat, potato, temporal dependency, schedule sensitivity, food security, climate adaptation, smallholder agriculture, observational study

What This Study Contributes — and Why It Matters

Irrigation science has, for decades, asked two questions: how much water, and how often? The exact time of day that water is delivered has been treated as a detail — irrelevant so long as the soil stays moist enough. Farmers, however, have long thought otherwise. We have spent four decades trying to take their intuition seriously.

This study makes four specific contributions to the scientific literature:

- It is the first study, to our knowledge, to document irrigation timing consistency as a distinct agronomic variable over a multi-decade observational period — covering 327 individual plants across three globally critical staple crops.
- It proposes a set of empirically derived, crop- and growth-stage-specific timing tolerance thresholds that offer a preliminary framework for thinking about scheduling risk — a framework that does not currently exist anywhere in extension guidance or FAO irrigation guidelines.

- It bridges two bodies of literature that have never been connected: plant circadian biology (which has established that plants have internal clocks and can anticipate environmental events) and irrigation scheduling science (which has entirely ignored within-day timing). The possibility that crops entrain to human-imposed watering routines is, as far as we know, untested.

- It identifies what may be a hidden vulnerability in food security assessments. A farming system can appear water-secure — volumetrically adequate — while carrying real yield risk if the timing of that water supply becomes unpredictable.

A note on what this study is not:

This is an observational hypothesis-generating study. It does not claim causal proof. It does not generalise beyond its West Bengal context without qualification. Its value lies in motivating a new line of inquiry — one that takes temporal consistency as seriously as water quantity and quality.

Study Registration and Declarations

Study type: Long-term observational field study (hypothesis-generating). Not a randomised controlled trial.

Data availability: Summary datasets are available from the corresponding author upon request. We are actively investigating deposition of de-identified plant-level records in a public repository — Zenodo (zenodo.org) or Dryad (datadryad.org) — and will update this statement with a DOI upon completion, in accordance with reviewer recommendations.

Ethics and consent: Observations were made on the authors' own managed fields and, where applicable, with the verbal consent of participating farming families. No human subjects research protocols apply.

Conflict of interest: The authors declare no competing interests, commercial affiliations, or financial relationships.

Funding: This research received no external funding. It was conducted independently over forty years of personal field management.

Author contributions: T.M. designed and conducted all field observations, maintained the primary records, and drafted the manuscript. S.S. reviewed observation records for consistency, contributed to interpretation, and critically revised the manuscript. Both authors approved the final version.

INTRODUCTION

What Farmers Know That Science Has Not Yet Measured

Ask an experienced farmer about irrigation, and they will usually mention three things: how much water, how often, and when the soil gets dry. This is also what the textbooks say. Extension leaflets produce careful charts on application volumes and frequency. Soil moisture sensors have become affordable even on small farms.

But there is a fourth dimension that rarely appears in the formal literature, even though farmers mention it constantly: the consistency of timing. Over decades of field observation, we heard the same remark in different forms, season after season. A wheat farmer told us in 2003 that his crop "expects water at 7 AM" — that delayed irrigation, even by a few hours, left the plants looking stressed despite moist soil underfoot. A paddy grower described how an equipment repair had forced him to switch from afternoon to morning irrigation, and how his rice had seemed unsettled for nearly two weeks afterward, that season's yield quietly below normal.

These stories are anecdotal. But they are also remarkably consistent — surfacing across different farmers, crops, seasons, and districts over four decades. We began, gradually, to document similar patterns ourselves in a more structured way. This paper is the record of that effort.

What Existing Science Tells Us

Plant water relations are among the most thoroughly studied areas in agricultural science. Researchers have mapped stomatal conductance, root water uptake, and the yield penalties of water stress during critical growth stages with considerable precision (Kramer & Boyer, 1995; Farooq et al., 2009).

A separate body of work concerns plant circadian biology — and here is where something interesting emerges. Plants possess internal clocks that regulate thousands of genes (McClung, 2006). These clocks synchronise to natural cues such as light and dark cycles (Hsu & Harmer, 2014), and plants with intact circadian systems show measurably higher photosynthetic efficiency than clock-disrupted mutants, apparently because they can anticipate dawn and prepare metabolically in advance (Dodd et al., 2005). Whether this capacity for anticipatory preparation might extend to human-imposed watering schedules is, to our knowledge, an entirely unstudied question.

Standard irrigation scheduling guidance (Doorenbos & Pruitt, 1977; Allen et al., 1998) focuses on water quantities and application frequencies. The clock time of delivery is treated as irrelevant so long as moisture thresholds are met. Our observations suggest this assumption may deserve a second look.

Our Study and Its Scope

Between 1985 and 2025, we maintained detailed field records on 327 staple crop plants: 145 paddy rice, 98 wheat, and 84 potato. These were not experimental plots with controlled conditions — they were working smallholder fields in West Bengal where we systematically recorded irrigation timing, plant responses, and yield outcomes across hundreds of growing seasons.

Four patterns emerged consistently:

- Crops maintained on consistent irrigation schedules for more than two to three weeks began showing what appeared to be anticipatory behaviour — stomata opening before water arrived, visible turgor changes preceding scheduled irrigation, and consistent stress signals at times when water was expected but delayed.
- Abrupt schedule changes were associated with measurable stress and yield reductions estimated at 15 to 35 percent, even when total water supply remained unchanged.
- Sensitivity varied with growth stage — plants were most vulnerable during flowering and grain or tuber filling, and far more tolerant during seedling establishment.
- Gradual schedule transitions — shifting timing by 15 to 30 minutes per day over one to two weeks — were associated with minimal disruption and near-normal final yields.

These are observational patterns, not controlled experimental results. Throughout this paper, we use language that reflects that distinction clearly. We present this as a hypothesis-generating contribution — a detailed field record intended to motivate the controlled studies that could confirm or refute what we found.

MATERIALS AND METHODS

Study Setting

All observations took place in West Bengal, India — a setting representative of Indo-Gangetic Plain smallholder agriculture, where paddy rice, wheat, and potato form the dominant crop rotation. The climate is subtropical monsoon (mean annual temperature ~26.5°C, annual rainfall ~1,600 mm concentrated in the June to September monsoon), with alluvial loam soils (pH 6.5 to 7.2). Observed fields ranged from 0.2 to 1.5 hectares — typical of smallholder operations across South Asia.

Observations were concentrated in three blocks of Burdwan district (approximately 23.5°N, 87.5°E) and two blocks of Nadia district (approximately 23.7°N, 88.4°E), both representative of the Gangetic alluvial plain. All fields received supplementary irrigation during the dry months of October to May.

We acknowledge upfront that a single agro-climatic zone limits how broadly our findings can be applied. The associations we describe may behave quite differently in temperate climates, arid conditions, fully rainfed systems, or large-scale mechanised agriculture. We return to this in Section 6.

Crops and Observation Approach

We focused on three crops chosen for their global importance and contrasting water use patterns:

- Paddy rice (Oryza sativa): varieties IR64, Swarna, and IET-4786 — all widely grown across South Asia and representative of regional production systems (IR64 is the most widely planted rice variety globally). 145 individual plants were tracked across 62 growing seasons under continuous flooding.
- Wheat (Triticum aestivum): varieties HD-2967 and PBW-343 alongside local landraces. 98 plants across 40 growing seasons, irrigated four to six times per season.
- Potato (Solanum tuberosum): varieties Kufri Jyoti and Kufri Chandramukhi alongside local cultivars. 84 plants across 47 growing seasons, irrigated every 7 to 10 days during tuber bulking.

Plants were identified by individual ID numbers recorded in field notebooks. Where possible, plants in the same field and season served as informal comparators — some maintained on a consistent schedule throughout (n=71 control plants), others subjected to timing changes. We cannot claim these groups were matched in all relevant respects; allocation was often determined by real-world circumstances rather than randomisation.

Irrigation Timing Protocols

For each crop cycle, a consistent irrigation schedule was established during the first 21 to 30 days after planting. Paddy was topped up daily at approximately 3:00 PM (±15 minutes); wheat every seven days at approximately 7:00 AM; potato every 8 to 10 days at approximately 8:00 AM. Timing was chosen to reflect local labour availability, not any physiologically optimal window.

After establishment, we recorded five categories of timing change:

- Gradual shift (n=78 plants): timing moved 15 minutes per day over 7 to 14 days.
- Moderate abrupt shift (n=95 plants): timing changed immediately by 2 to 4 hours.
- Severe abrupt shift (n=61 plants): timing changed immediately by 6 to 8 hours.
- Random timing (n=43 plants): irrigation at varying times with no discernible pattern.
- Schedule cessation (n=50 plants): fixed schedule abandoned; irrigation based on visual soil moisture assessment only.

Many of these perturbations were not deliberately imposed — they arose from real-world events like pump failures, electricity restrictions, and labour shortages, and were recorded opportunistically. This gives the data ecological realism, but it also means there was no randomisation and no true control over perturbation type.

What We Measured and How

We did not have access to electronic sensors or laboratory equipment. All observations were standardised visual and manual records taken three times daily (7 AM, 12 PM, 4 PM):

- Leaf turgor: rated 0 to 5 (0 = fully turgid; 5 = severe wilting), using standard field assessment conventions.

- Stomatal status: estimated under a hand lens on five leaves per plant (open / partially open / closed).
- Leaf colour changes: chlorosis, tip burn, and early senescence.
- Growth rate: stem height measured weekly.

Weekly records noted phenological stage, stress symptom type, and pest or disease incidence. At harvest, grain or tuber yield per plant, 1,000-grain weight (cereals), average tuber size (potato), and visual quality were recorded. Soil moisture was monitored gravimetrically at 15 cm depth before and after each irrigation event — primarily to confirm that stress was not attributable to actual water shortage.

We acknowledge that the primary observer (T.M.) conducted the vast majority of field visits, which introduces the possibility of systematic observer bias. The second author (S.S.) periodically reviewed records for consistency but was not present for most observations. This limitation cannot be corrected retrospectively.

Records and Data Management

Primary records were maintained in 127 bound field notebooks, with daily entries recording date, time, weather, irrigation timing, plant observations by ID number, and field notes on equipment or labour events. From 2005, data were transcribed into spreadsheets for quantitative analysis, though the original notebooks remain the primary record. Photographic documentation began in 1998.

We recognise that this documentation approach, while thorough by field standards, does not meet the archival requirements of modern experimental science. We are completing the process of depositing de-identified plant-level data in a public repository (Zenodo or Dryad) and will update the Data Availability statement with the resulting DOI before final publication.

Statistical Methods

Given the observational nature of the data and the many uncontrolled variables, we used conservative statistical approaches rather than models that might imply greater precision than the data support.

Critical timing deviation (ΔT_{crit}) was defined empirically as the maximum schedule shift beyond which more than 50% of observed plants showed measurable stress within seven days — identified by comparing outcomes across perturbation magnitudes, not by fitting a formal dose-response model. Uncertainty in these estimates is substantial.

Yield loss was calculated as a percentage relative to control plants. Growth stage sensitivity was assessed by grouping perturbations by phenological stage and comparing stress response rates using one-way ANOVA ($p < 0.05$; R version 4.2.1). We did not apply mixed-effects models to account for repeated measures across seasons and plants — a methodological limitation that future controlled studies should address with more sophisticated approaches.

A note on statistical power for researchers designing follow-up studies: based on the coefficient of variation in our data (approximately 20%), a sample size of $n=10$ plants per treatment would provide roughly 80% power to detect a 15% yield reduction at $\alpha=0.05$. We offer this as a planning estimate, not a formal power calculation.

RESULTS

Anticipatory Responses Under Consistent Scheduling

Across all three crops, after 14 to 21 days of consistent irrigation timing, plants began showing what appeared to be anticipatory physiological behaviour. We describe these observations carefully; they are based on field-level assessment, and we cannot rule out alternative explanations.

In paddy rice, stomata on 87% of observed plants ($n=126$) began opening an estimated 30 to 45 minutes before the scheduled 3 PM irrigation — even on overcast days when neither temperature nor light conditions would normally drive afternoon stomatal opening. On days when we deliberately withheld the scheduled irrigation, stomata still opened at the expected time, then gradually closed over the following 60 to 90 minutes. This pattern was confirmed across 15 tagged plants observed in three consecutive seasons (2017 to 2019). Visual stomatal assessment via hand lens carries inherent subjectivity, and we acknowledge this.

In wheat, visible guttation — water droplets at leaf margins — began appearing around 6:00 to 6:30 AM on irrigation days, roughly 30 to 60 minutes before the scheduled 7 AM watering. This did not occur on non-irrigation days and was absent in plants maintained on randomised schedules. We interpret this cautiously, as guttation can be influenced by overnight humidity and root pressure independent of scheduling.

Potato showed the clearest pattern. During tuber bulking, plants on an 8 AM watering schedule showed measurably higher leaf turgor at 7:00 to 7:30 AM compared with early morning readings, even when overnight soil moisture was unchanged. When we were forced to shift irrigation to 6 PM due to electrical supply restrictions (12 plants, 2012), the morning turgor pattern persisted for four to six days before gradually fading. A new turgor peak then developed in the late afternoon, approximately two to three hours before the new irrigation time — suggesting that plants can re-adjust, but require roughly two weeks to do so.

Stress Responses Following Schedule Disruption

When established schedules were disrupted, we observed consistent patterns of physiological stress across all three crops. These are associations, not causal relationships; seasonal variation and other uncontrolled factors may have contributed.

Following a three-hour delay in paddy irrigation (3 PM shifted to 6 PM), subtle wilting appeared around the time of the previous irrigation on Day 1, resolving once water arrived. By Days 2 to 3, leaf rolling was visible and persisted longer. By the end of the first week, growth rate had slowed, older leaves had begun to yellow, and standing water level dropped faster — possibly indicating reduced water use efficiency. By Day 14, new leaves were emerging smaller than those of control plants, and flowering was delayed by three to five days. At harvest, grain yield in affected plants averaged 22% below controls (range 15 to 28%; n=18). Soil moisture throughout this period had remained at or above field capacity.

In wheat, a four-hour delay produced no visible effect on Day 1 but led to transient flag-leaf wilting on subsequent mornings. By Days 6 to 10, lower leaf senescence had accelerated and tillering had slowed. Flowering was delayed by four to six days. Final grain yield averaged 18% below controls (range 12 to 26%; n=14), with 1,000-grain weight reduced by 8 to 12%.

The potato response was the most dramatic. A pump failure in 2008 forced overnight irrigation for two weeks — a shift of approximately 10 hours affecting nine plants. Within three to seven days, upper leaf chlorosis appeared despite adequate nitrogen levels. Tuber initiation was delayed by roughly one week. Final tuber yield was 31% below controls (range 24 to 38%), with a high proportion of small and misshapen tubers. We note that this was an emergency situation with multiple co-occurring disruptions, making it particularly difficult to attribute the outcome to timing alone.

Timing Tolerance Thresholds by Crop and Growth Stage

After compiling hundreds of observed schedule disruptions over four decades, patterns in the severity of response became apparent. Table 1 summarises these rough empirical thresholds — the point at which more than 50% of observed plants showed visible stress within seven days. These are field-level estimates with considerable uncertainty, not precise physiological constants.

Crop	Growth Stage	ΔTcrit (est.)	n (obs.)	Stress > 50% if exceeded	Yield Impact
Paddy Rice	Seedling / transplanting	±6–8 hrs	34	~35%	Minimal (<5%)

	Vegetative / tillering	±4–6 hrs	52	~58%	Moderate (8–15%)
	Flowering / panicle emergence	±1–2 hrs	41	~87%	Severe (20–35%)
	Grain filling	±2–3 hrs	38	~73%	High (15–28%)
Wheat	Seedling establishment	±8–10 hrs	28	~29%	Minimal (<5%)
	Vegetative / tillering	±5–7 hrs	36	~53%	Moderate (10–18%)
	Flowering / anthesis	±2–3 hrs	22	~82%	Severe (18–32%)
	Grain filling	±3–4 hrs	31	~65%	High (12–26%)
Potato	Sprouting / emergence	±7–9 hrs	25	~32%	Minimal (<8%)
	Vegetative growth	±5–6 hrs	29	~55%	Moderate (10–20%)
	Tuber initiation	±2–3 hrs	18	~89%	Severe (24–38%)
	Tuber bulking	±3–5 hrs	27	~67%	High (15–31%)

Table 1. Estimated critical irrigation timing deviation thresholds (ΔTcrit) and associated yield impacts by crop and growth stage. Values represent field-level estimates based on observational data; confidence intervals could not be calculated reliably due to uncontrolled covariates. All yield impacts are relative to control plants maintained on an uninterrupted schedule.

Three patterns stand out. First, all three crops appeared most vulnerable during reproductive stages — consistent with what is known about the metabolic demands of flowering and grain or tuber development (Farooq et al., 2009). Second, seedlings showed far greater tolerance, possibly because entrainment to a timing routine requires repeated exposure before it takes hold. Third, potato was consistently more sensitive than wheat across growth stages, though this may partly reflect differences in our observation frequency rather than true physiological differences.

Schedule Deviation and Yield Loss

Table 2 summarises observed associations between the magnitude of schedule shifts and estimated yield loss. These figures come from observational data spanning variable weather, soil, and management conditions. The ranges reflect real variability, not measurement precision.

Schedule Shift	Paddy Rice	Wheat	Potato	Average Across Crops
±1–2 hours	3–8% (n=23)	2–6% (n=18)	4–9% (n=15)	~3–8%
±2–4 hours	12–22% (n=31)	8–18% (n=24)	14–25% (n=21)	~11–22%
±4–6 hours	22–35% (n=26)	16–28% (n=19)	28–42% (n=18)	~22–35%
±6–8 hours	35–52% (n=14)	24–38% (n=12)	38–58% (n=11)	~32–49%
>8 hours or random	45–68% (n=9)	35–51% (n=8)	52–74% (n=7)	~44–64%

Table 2. Estimated yield loss relative to control plants by schedule deviation magnitude. Sample sizes are small in larger-deviation categories; interpret with caution.

To put these numbers in practical context: a smallholder with 0.5 hectares of paddy producing 3 tonnes per hectare earns roughly ₹30,000 to 40,000 per season. A 22% yield loss represents approximately ₹6,600 to 8,800 — more than a month's income for many rural households. We offer this calculation to motivate scientific attention, not as a validated economic model.

Recovery Capacity

A key practical question is whether crops can re-adapt to a new schedule after disruption. Our observations suggest they can — but the outcome depends critically on how the transition is managed.

Transition Type	n (plants)	Stress Duration (days)	Full Recovery?	Final Yield (% of control)
Gradual (15–30 min/day)	32	0–3	Yes	94–99%
Abrupt shift, stable new schedule	41	7–15	Partial	85–93%
Abrupt large shift (>6 hours)	23	10–25	Rare	62–78%
Repeated random shifts	19	Chronic	No	38–55%

Table 3. Observed recovery outcomes by schedule transition type. Sample sizes are modest; results are based on observational, not experimental, conditions.

In a deliberate exercise on 32 paddy plants in 2016, we shifted irrigation timing from 3 PM to 9 AM over 14 days by advancing the schedule 25 to 30 minutes each day. No visible stress symptoms appeared during the transition, and final yield was 97% of controls. By contrast, an abrupt four-hour shift imposed on wheat in 2018 produced visible stress for 7 to 15 days before plants stabilised, with final yield around 89% of controls. The worst outcomes consistently arose from repeated random changes, where plants appeared never to stabilise and chronic stress persisted until harvest.

Sensitivity by Growth Stage

Across all three crops, apparent timing sensitivity followed the same arc: lowest during seedling establishment, rising through vegetative growth, peaking sharply during flowering and grain or tuber filling, then declining as maturity approached. This pattern is consistent with what plant physiology would predict — reproductive stages involve high and precisely coordinated metabolic demands (Farooq et al., 2009) — though we cannot confirm the mechanism from observational data alone.

The practical implication is that the consequences of schedule disruption are not evenly distributed across the season. A three-hour delay that causes minimal harm during vegetative growth may be associated with severe yield loss if it falls during flowering. This asymmetry means that the risk of timing disruption is concentrated into relatively narrow windows — a point with practical implications for when, in the season, schedule consistency matters most.

DISCUSSION

What the Patterns Might Mean

We want to be honest about what our data can and cannot establish. We have documented associations between irrigation timing shifts and apparent yield reductions. We have not demonstrated a causal mechanism. The hypotheses below are speculative — informed by the literature but not validated by our own experimental work. We offer them to frame future investigation, not to assert conclusions.

One plausible explanation involves metabolic coordination under temporal predictability. Plants are constantly making resource allocation decisions: when to open stomata, how to mobilise carbohydrates, when to invest in roots versus shoots. If irrigation timing is predictable, a plant might commit to specific resource states in anticipation of water arrival — opening stomata widely when water is expected, conserving energy when it is not. Circadian biology provides mechanistic support for this kind of temporal optimisation: plants with functional internal clocks show higher water use efficiency than clock-disrupted mutants, apparently because they can anticipate and prepare for environmental shifts (Dodd et al., 2005). Whether a human-imposed irrigation schedule can entrain similar anticipatory physiology is the key empirical question our data cannot answer.

A second possibility involves hormonal rhythm disruption. Abscisic acid (ABA), which mediates drought stress responses, shows circadian oscillations even under constant conditions (Covington & Harmer, 2007). If consistent irrigation timing entrains these oscillations so that ABA drops reliably before watering, an abrupt schedule change might create a mismatch — ABA rising when water is actually available, unnecessarily suppressing growth. The two- to four-day lag we often observed between schedule changes and visible stress symptoms is consistent with the time it might take for hormonal misalignment to cascade into observable effects. But we have no hormonal measurements to test this.

A third, more speculative possibility is that root system dynamics and rhizosphere microbial communities — known to follow diurnal activity patterns (Berendsen et al., 2012) — might also entrain to irrigation timing, such that schedule changes disrupt plant-microbe coordination in ways that reduce nutrient uptake or stress tolerance. This would require molecular investigation to evaluate.

There is a suggestive parallel in animal science worth noting: dairy cows produce less milk when feeding times vary day-to-day, even when total feed quantity is unchanged (DeVries et al., 2005). Temporal consistency effects are already recognised in animal production systems. The plant science community has not yet investigated them with comparable rigour.

Addressing Reviewer Concerns Directly

We would rather address the core concerns raised in peer review directly here, rather than bury them in a limitations appendix.

On experimental control: the reviewers are right. Our observational design cannot exclude confounding variables — weather variation, soil heterogeneity, pest pressure, and observer effects are all plausible alternative explanations for the associations we observed. We have taken care throughout this paper to describe patterns as associations rather than causal relationships, and we strongly support the call for controlled experiments. Four decades of systematic field observation can constitute a credible hypothesis-generating contribution — the kind that has preceded laboratory validation in many fields — but it does not constitute proof.

On the magnitude of reported yield losses: the reviewers find our estimates (15 to 35% for relatively modest timing shifts) larger than expected. We can only report what we observed, while acknowledging that uncontrolled variables may account for some of this. Real farm conditions involve multiple co-occurring stresses; it is possible that timing shifts compound with minor stressors in ways that produce larger aggregate effects than a controlled study would find. Only adequately replicated experiments will resolve this.

On mechanistic evidence: we have none to offer from this study. The proposed mechanisms are entirely speculative. Controlled experiments measuring ABA and cytokinin dynamics, circadian clock gene expression, and stomatal conductance under timed versus randomised schedules would be needed to evaluate any of our hypotheses. We have tried throughout this paper to be explicit about the boundary between what we observed and what we are speculating.

Climate Change and Food Security Implications

If the associations we observed reflect genuine physiological phenomena, the food security implications deserve serious attention. Climate change is increasing the temporal unpredictability of monsoon onset, generating dry spells within wet seasons, and making river flows and energy supply for irrigation pumps less reliable (Krishnan et al., 2020; Lobell et al., 2011). Labour market changes in rural South Asia are reducing the predictability of farm labour availability. Energy rationing increasingly restricts pump operation to time windows that shift seasonally.

All of these forces make irrigation timing disruptions more likely, even in systems where total water availability appears adequate. If timing-related yield losses are real, they represent a hidden vulnerability — one invisible to assessments based purely on volumetric water security calculations.

Farmers in our study area are already noticing the change. As one put it:

"The weather no longer follows a schedule, so we cannot follow one either."

If crops are genuinely sensitive to timing consistency, then climate adaptation strategies focused only on water quantity or heat tolerance may be missing a meaningful dimension.

Connections to the Broader Literature

Our findings sit at the intersection of three bodies of literature that have not previously been connected. Plant circadian biology establishes that plants have endogenous timing mechanisms that affect water use efficiency (Dodd et al., 2005; McClung, 2006) — but this work focuses on natural light cycles in controlled settings, not on human-imposed irrigation routines. Irrigation scheduling science provides detailed guidance on volumes and frequencies (Allen et al., 1998) but treats within-day timing as irrelevant. Crop physiology research on water stress (Farooq et al., 2009) focuses almost exclusively on water deficit — the quantity dimension. The possibility that crops can experience what we might call timing stress under adequate total water supply appears to be essentially unstudied.

This is the gap our work is intended to highlight.

Pathways to Validation

Three types of investigation would substantially clarify whether the patterns we observed reflect real physiological phenomena:

- Controlled greenhouse experiments: grow matched populations of wheat or paddy under identical conditions, establish consistent watering timing for 30 days, then impose standardised schedule shifts of varying magnitudes while maintaining total water volume. Measure stomatal conductance (portable porometer), photosynthetic rate, leaf water potential, ABA concentrations, and final grain yield. Recommended minimum measurements: (a) stomatal conductance at 30-minute intervals before and after schedule shifts; (b) leaf ABA concentration via ELISA at 0, 3, 7, and 14 days post-shift; (c) circadian clock gene expression (CCA1, TOC1, LHY) via qPCR; (d) photosynthetic rate; (e) final grain/tuber yield and 1,000-grain weight. All treatments should include at least n=10 replicates with random assignment.

- Multi-site field trials: collaborate with agricultural research stations in different countries and climate zones to test whether the patterns replicate or are specific to our context.

- Molecular and hormonal assays: sample ABA, cytokinin, and circadian clock gene expression in plants before and after schedule changes. If hormone concentrations and clock gene rhythms show systematic disruption correlating with schedule shifts, the mechanistic hypotheses gain empirical support.

We are not in a position to conduct these studies ourselves. We present them as a research agenda for the wider community.

Key Open Questions for Controlled Investigation:

1. Is anticipatory stomatal opening real or an artefact of uncontrolled variables? (Controlled greenhouse study, 30 plants fixed vs. 30 random schedule, porometer measurements) | 2. Are the yield losses of 15-35% reproducible under controlled conditions? (Multi-replication greenhouse trial, random assignment, full yield *accounting) | 3. What is the hormonal basis, if any? (ABA/cytokinin time-course before and after schedule shifts, clock gene expression via qPCR) | 4. Do the thresholds hold across climate zones? (Multi-site field trials, standardised perturbation protocol)*

Preliminary Practical Guidelines

Important caveat:

The following guidance is based on observational patterns, not validated recommendations. These should be treated as hypotheses for farm-level testing rather than established best practice. Farmers and extension workers should exercise independent judgment and account for local conditions.

Quick-Reference Timing Tolerance Estimates

Crop	Seedling Stage	Vegetative Stage	Flowering Stage	Grain / Tuber Filling
Paddy Rice	~±6 hours	~±4 hours	~±1 hour (HIGH RISK)	~±2 hours
Wheat	~±8 hours	~±5 hours	~±2 hours (HIGH RISK)	~±3 hours
Potato	~±7 hours	~±5 hours	~±2 hours (HIGH RISK)	~±3 hours

Table 4. Preliminary estimated safe timing deviation limits based on observational data. Rough guidelines only; exceeding them may be associated with yield losses exceeding 10%. Not validated in controlled experiments.

Scheduling Principles

- Establish consistent timing early. The first two to three weeks after planting appear to set the timing expectations that plants may rely on throughout the season. Choose an irrigation time that can realistically be maintained through critical growth stages.
- Minimise deviations during reproductive stages. If changes are unavoidable, our observations suggest it is better to make them during vegetative growth. Changes during flowering or grain filling appear to carry the greatest yield risk.
- Use gradual transitions wherever possible. Shifting timing by 15 to 20 minutes per day appeared in our observations to allow plants to adjust with minimal disruption — compared with abrupt changes that caused visible stress for one to two weeks.
- Recognise timing stress versus water deficit. If leaves wilt at specific times of day despite moist soil, timing disruption may be a more likely explanation than water shortage. Adding more water at random times may not help.
- Consider the economics of schedule consistency. In our rough calculations, the labour cost of maintaining consistent timing was often outweighed by potential yield benefits. This will vary by crop value, farm size, and local labour costs.

When These Guidelines Do Not Apply

We stress again: these observations come from one agro-climatic region. They may not apply in drip or automated sprinkler systems (where timing consistency is already mechanically enforced), fully rainfed systems, arid or cold temperate climates, large-scale mechanised agriculture, or situations where water quantity itself is severely limited.

Regional Scope and Generalisability

All observations in this study come from West Bengal, India, under smallholder flood and tube-well irrigation management. We believe this context is broadly representative of the Indo-Gangetic Plain, where similar crops, soils, and irrigation systems predominate. But we are cautious about claiming wider generalisability without independent validation.

The physiological mechanisms we hypothesise — if they exist — should in principle operate wherever these crops are grown, since they would be rooted in plant circadian biology and metabolic coordination rather than region-specific traits. IR64 and HD-2967, the varieties we primarily studied, are grown across South Asia and beyond. But the magnitude of timing effects, the relevant tolerance windows, and the practical management implications could differ substantially in year-round humid tropical climates, cold temperate systems, or fully mechanised agriculture with drip or pivot irrigation.

We encourage researchers in other regions to document whether similar associations appear in their contexts, particularly under controlled conditions. Multi-site collaboration would substantially strengthen — or refute — the patterns we describe here.

For policy, we note that if timing consistency proves important, the implications extend to irrigation system design, energy policy (time-of-day electricity restrictions that force farmers to change pump schedules seasonally), and extension training. These are areas where change could be beneficial — but we recommend waiting for controlled experimental validation before advocating specific policy changes.

CONCLUSIONS

After forty years of field observation across 327 staple crop plants in West Bengal, a recurring pattern is clear: irrigation timing consistency appears to be associated with plant physiology and yield outcomes in ways that existing agricultural science frameworks do not capture. Plants maintained on consistent schedules for two to three weeks appear to develop anticipatory physiological responses. Abrupt disruption of those schedules is associated with measurable stress and yield losses — even when total water supply remains unchanged.

We are clear about what this study is. It is a long-term observational record from a single agro-climatic region, collected without randomisation, experimental controls, or laboratory instrumentation. It cannot establish causal relationships. It is a hypothesis-generating contribution, not a definitive investigation.

What it does offer is forty years of consistent, detailed field-level documentation of patterns that we believe deserve scientific attention. The consistency of these patterns across crops, seasons, and types of scheduling disruption — and their alignment with mechanisms that circadian plant biology makes plausible — suggests they are not merely artefacts of observer bias or seasonal variation.

Three things are needed to take this forward: controlled greenhouse experiments to test whether timing-dependent physiology is real; multi-site field trials to assess robustness across environments; and molecular studies to identify the underlying mechanisms. We hope this record provides both the motivation and the empirical grounding to support those investigations.

Farmers have long said that plants remember their watering schedule. We spent four decades trying to document whether that folk wisdom has a factual basis. The patterns we found are consistent with it being true. The next step is to find out definitively.

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This research was conducted without institutional affiliation, grant funding, or access to modern laboratory equipment. We acknowledge that these constraints limit the sophistication of our methods — but also reflect a reality of scientific observation: important questions can sometimes be approached through sustained, systematic work even with minimal resources.

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REFERENCES

1. Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization, Rome.
2. Berendsen, R.L., Pieterse, C.M., & Bakker, P.A. (2012). The rhizosphere microbiome and plant health. Trends in Plant Science, 17(8), 478–486.
3. Covington, M.F., & Harmer, S.L. (2007). The circadian clock regulates auxin signaling and responses in Arabidopsis. PLoS Biology, 5(8), e222.
4. DeVries, T.J., von Keyserlingk, M.A., & Beauchemin, K.A. (2005). Frequency of feed delivery affects the behavior of lactating dairy cows. Journal of Dairy Science, 88(10), 3553–3562.
5. Dodd, A.N., Salathia, N., Hall, A., Kévei, E., Tóth, R., Nagy, F., et al. (2005). Plant circadian clocks increase photosynthesis, growth, survival, and competitive advantage. Science, 309(5734), 630–633.
6. Doorenbos, J., & Pruitt, W.O. (1977). Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24. Food and Agriculture Organization, Rome.
7. FAO (2020). FAOSTAT statistical database. Food and Agriculture Organization of the United Nations.
8. Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S.M. (2009). Plant drought stress: effects, mechanisms and management. Agronomy for Sustainable Development, 29(1), 185–212.
9. Hsu, P.Y., & Harmer, S.L. (2014). Wheels within wheels: the plant circadian system. Trends in Plant Science, 19(4), 240–249.
10. Kramer, P.J., & Boyer, J.S. (1995). Water relations of plants and soils. Academic Press, San Diego.
11. Krishnan, R., Sanjay, J., Gnanaseelan, C., Mujumdar, M., Kulkarni, A., & Chakraborty, S. (2020). Assessment of climate change over the Indian region. Springer Nature, Singapore.
12. Lobell, D.B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. Science, 333(6042), 616–620.
13. McClung, C.R. (2006). Plant circadian rhythms. The Plant Cell, 18(4), 792–803.
14. Muthayya, S., Sugimoto, J.D., Montgomery, S., & Maberly, G.F. (2014). An overview of global rice production, supply, trade, and consumption. Annals of the New York Academy of Sciences, 1324(1), 7–14.
15. Shiferaw, B., Smale, M., Braun, H.J., Duveiller, E., Reynolds, M., & Muricho, G. (2013). Crops that feed the world 10. Food Security, 5(3), 291–317.