The Temporal–Lifespan Scaling Law: A Universal Principle Linking Plant Longevity to Routine Timing Tolerance

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DOI: https://doi.org/10.51584/IJRIAS.2026.11050045

Received: 01 May 2025; Accepted: 06 May 2026; Published: 27 May 2026

ABSTRACT

Plants are well known to possess internal biological clocks that regulate daily cycles of growth, water uptake, and gas exchange. What has received far less attention is what happens when cultivated plants become accustomed to the fixed, human-imposed schedules that define modern agriculture and horticulture—and what happens when those schedules are disrupted. This paper reports findings from a 40-year field study (1985–2025) tracking 1,247 individual plants across 68 species, ranging in lifespan from 45-day radishes to long-lived banyan trees estimated to survive several centuries.

Plants maintained under consistent daily or weekly care routines for more than 60 days developed recognisable anticipatory behaviour: stomata opened before scheduled irrigation arrived, hydraulic pressure in stems rose ahead of watering events, and metabolic processes were primed in advance of expected inputs. When these routines were abruptly changed—even while water volume and nutrients remained unchanged—physiological stress followed in the majority of observed plants. Among fast-growing herbs, 79% showed measurable decline within approximately two weeks; among seasonal crops, 68% within three weeks; among short-lived perennials, 61% within four weeks.

Across the full dataset, the maximum tolerable timing deviation (ΔT_{crit}) before physiological decline appeared to scale with species characteristic lifespan (L) according to the empirical relationship $\Delta T_{crit} \approx 0.019 \times L^{0.98}$ ($R^2 = 0.82$, $p < 0.001$, $n = 68$), a pattern we term the Temporal–Lifespan Scaling Law. This held across all growth forms, photosynthetic pathways, and taxonomic families in the dataset. Crops such as tomato and chilli that are routinely harvested early showed timing tolerances consistent with their full evolutionary lifespan rather than their cultivation period, suggesting that temporal sensitivity reflects developmental programming.

These findings point to temporal predictability as a meaningful and underappreciated dimension of plant physiological stability under cultivation. The practical implications span irrigation scheduling, transplantation protocols, urban forestry, climate vulnerability assessment, and plant breeding. We propose that this body of phenomena warrants a dedicated research focus, which we call chronoecology: the systematic study of how plants internalise, anticipate, and depend upon temporal structure in their environments.

Keywords: temporal entrainment, circadian dependency, chronoecology, scaling law, agricultural timing, irrigation scheduling, plant physiology

Scope Statement

This paper addresses a gap at the intersection of plant chronobiology, agricultural physiology, and ecological scaling theory. Circadian biology has established that plants possess endogenous oscillators that synchronise with natural light–dark cycles. What remains almost entirely undocumented is what happens physiologically when those oscillators entrain to the highly predictable, schedule-driven routines of cultivated settings—and whether disruption of such entrainment constitutes a meaningful form of stress. Our 40-year field dataset, spanning five orders of magnitude in species lifespan, offers what we believe is the first quantitative framework for understanding how timing sensitivity relates to organismal longevity. Broader replication will be essential to establish its generality. The practical relevance extends from precision irrigation and nursery transplantation to climate change vulnerability and plant breeding for temporal resilience.

Novelty Statement

This study presents several contributions not previously reported in the peer-reviewed literature, to our knowledge. First, we document through systematic longitudinal observation that plants under consistent cultivation routines form measurable physiological dependencies on the timing of care inputs, exhibiting anticipatory responses and declining when schedules change even while material resources remain adequate. Second, we identify a power-law scaling relationship linking timing tolerance to lifespan across a broad range of angiosperm life histories.

Third, we show that crops on abbreviated schedules retain timing sensitivity consistent with their evolutionary lifespan. Fourth, we propose the temporal desynchronisation cascade as a conceptual model for a mechanistically distinct form of plant stress. Fifth, we introduce chronoecology as a formal research domain bridging chronobiology, agriculture, and ecology.

INTRODUCTION

Experienced growers often notice something that is difficult to explain in purely chemical or physical terms. A plant that has been watered at seven o'clock every morning for several months begins, over time, to look expectant before the water arrives. Its leaves orient slightly. Its stomata open a fraction wider than soil moisture alone would justify. And when the schedule is disrupted, the plant's response can seem disproportionate to the actual deficit—as though something beyond thirst has been violated. Horticulturists have described versions of this observation for generations, usually in language that mainstream plant science has been cautious to accommodate [1–3].

The science of plant circadian biology has established beyond reasonable doubt that species across the botanical kingdom carry endogenous oscillators governing daily cycles of stomatal conductance, photosynthetic capacity, leaf movement, and hormone secretion [4–6]. These internal clocks synchronise with natural light–dark transitions through photoreceptor pathways involving phytochromes and cryptochromes, conferring adaptive advantages that include anticipating dawn, optimising carbon fixation, and coordinating developmental events with seasonal photoperiods [7–9]. This body of work, developed largely in laboratory settings, has revealed the molecular architecture of the plant clock in considerable detail [25, 26].

What remains far less studied is the consequence of long-term entrainment to the rigid, human-determined temporal routines of cultivated settings. Across billions of cultivated plants worldwide, watering events follow labour schedules rather than rainfall patterns. Greenhouse lighting cycles follow programmable timers. Fertiliser applications, pruning events, and the presence of caretakers recur with a regularity that natural ecosystems never provide. In botanical gardens, ancient temple groves, or well-tended orchards, these patterns may persist across decades or human generations.

The question this study has pursued over four decades of field observation is conceptually simple: do plants become physiologically dependent on artificial temporal routines in ways that compromise their stability when those routines change? The answer carries practical urgency. Global agriculture increasingly relies on precision irrigation optimised for water-use efficiency but rarely designed with plant temporal expectations in mind [13, 14]. Climate change is introducing unprecedented unpredictability into rainfall timing and seasonal patterns [15, 16]. Urban forestry programmes transplant nursery-raised trees, accustomed to metronomic watering, into the temporal irregularity of city streets [17].

Here we report that across 1,247 plants representing a broad sweep of angiosperm life histories, a consistent empirical relationship appears to link species lifespan to tolerance for routine timing deviations. We present this as an observational pattern warranting experimental investigation, rather than an established mechanistic law, and we discuss its implications for plant science and agricultural practice.

MATERIALS AND METHODS

Study Design, Duration, and General Approach

This work represents systematic field documentation conducted continuously from March 1985 through November 2025 (approximately 40.7 years) across multiple cultivation sites in West Bengal, India (approximately 22°34′N, 88°22′E). The study was observational in character: it tracked naturally occurring variation in plant responses to timing perturbations arising through ordinary horticultural practice, seasonal changes in caretaker availability, infrastructure events, and—from 1997 onwards—deliberately introduced small-scale timing modifications designed to test emerging patterns. We acknowledge that this design, while affording longitudinal depth and species breadth, limits the causal inferences that can be drawn; controlled experimental replication under laboratory conditions is an important next step.

Throughout all observations, water volume delivered, soil moisture levels, and nutrient availability were held as constant as field conditions allowed; only the timing of input delivery was permitted to vary. Standardised measurement protocols are described in Section 2.2. Observations were recorded in bound field notebooks using standardised data fields. From 2003 onwards, records were digitised into spreadsheet format. The dataset comprises 1,247 individual plant-observation records across 68 species.

Environmental Standardisation and Measurement Protocols

A key methodological challenge was maintaining consistency of care quality across four decades while allowing only timing to vary. Soil moisture was measured using calibrated tensiometers, with readings logged at each irrigation event from 1992 onward; prior to 1992, assessment relied on standardised tactile and visual criteria documented in the field notebooks. Water volumes were measured using calibrated watering cans or flow meters for drip systems. Nutrient status was assessed through annual soil tests at each site, with supplementation adjusted to maintain comparable fertility. Canopy light conditions were recorded seasonally to flag major changes arising from infrastructure or vegetation changes.

We acknowledge that these measures, while systematic, cannot fully replicate controlled laboratory conditions. Sources of uncontrolled variation—including inter-annual climate variability, subtle differences in soil structure across plots, and the inherent limitations of human observation over long periods—represent genuine constraints on interpretation and are discussed in Section 4.1.

Plant Material and Life History Coverage

To assess whether temporal sensitivity patterns are general or restricted to particular taxonomic groups or growth forms, we tracked species spanning the widest feasible range of longevities: five orders of magnitude from 45-day radishes to banyans with estimated lifespans of several centuries.Table 1 summarises coverage across life history categories. The diversity of growth forms, photosynthetic pathways (C_3 and C_4), root architectures, and geographic origins was intentional, allowing tests of whether any observed patterns reflect universal principles or are confounded by particular biological characteristics.

Life History Category	Species (n)	Individuals (n)	Mean Lifespan (days)	Example Species
Fast annual herbs (2–3 mo.)	8	154	66	Coriander, radish, spinach
Seasonal crops (3–6 mo.)	7	191	125	Rice, wheat, okra
Short-lived perennials (1.5–3 yr)*	8	189	776	Tomato, chilli, basil
Medium perennials (10–50 yr)	16	327	11,247	Jasmine, hibiscus, jade plant

Fruit trees (40–150 yr)	15	257	38,690	Mango, guava, coconut
Ancient trees (150–600 yr)	14	213	146,000	Banyan, peepal, neem

Table 1. Species coverage across life history categories. *Lifespan values represent biological potential rather than typical cultivation period (see Section 2.4).

Lifespan Estimation: Agricultural Practice Versus Biological Potential

Species such as tomato, chilli, and eggplant are routinely cultivated as annuals but are biologically capable of multi-year survival. We used biological potential lifespan rather than cultivation period for these species, estimated from direct observation of individuals maintained beyond normal harvest dates, horticultural literature on perennial cultivation, and farmer reports of volunteer plants surviving multiple seasons. Our reasoning is that temporal integration capacity is likely governed by evolutionary life history programming rather than by arbitrary harvest schedules. A tomato plant is developmentally a short-lived perennial regardless of when it is uprooted.

We acknowledge this decision introduces interpretive complexity. Sensitivity analyses using alternative lifespan estimates, including cultivation period, are reported in Section 3.3; the core scaling relationship is robust across all alternatives tested.

Temporal Conditioning Protocol

Plants were considered entrained to a routine when a particular environmental input occurred at consistent times for a sustained conditioning period. Minimum conditioning durations were: 60 days for annual herbs and fast crops; 90–180 days for seasonal crops and short-lived perennials; 6–12 months for medium perennials; and 1–5 years for trees. These thresholds were established empirically during the early years of the study, based on the observation that shorter conditioning periods produced more variable and often absent anticipatory responses. Routines were classified by precision: daily fixed-hour routines (±15 minutes of the same clock time each day), weekly fixed-day routines, and bi-weekly or monthly routines at regular intervals.

Timing Perturbations

Perturbations arose through three mechanisms. Natural perturbations ($n = 437$ cases) included changes in caretaker work schedules, seasonal shifts, temporary infrastructure disruptions, and monsoon flooding. Deliberate test perturbations ($n = 318$ cases), introduced systematically from 1997 onwards, advanced or delayed routine timing by increments of 15 minutes to one full day in subsets of plants. Transplantation-induced perturbations ($n = 492$ cases) arose when relocating plants changed the effective timing schedule. The distinction between perturbation types is noted in the dataset; no systematic differences in response patterns were observed across types.

Outcome Documentation

Following any timing perturbation, plants were monitored using standardised observational criteria spanning three temporal horizons. Acute responses (24–72 hours): stomatal behaviour anomalies, leaf orientation changes, and anticipatory wilting during expected irrigation times. Subacute responses (1–4 weeks): chlorosis not attributable to nutrient deficiency (confirmed by soil testing), growth arrest, increased susceptibility to fungal infection, and flower bud or fruit drop. Chronic decline (1–6 months): progressive senescence, branch-tip dieback, root rot, and mortality. Observers used a four-point severity scale (absent, mild, moderate, severe) at standardised intervals, with inter-observer consistency reviewed at annual field training sessions.

Definition of Critical Timing Deviation (ΔT_{crit})

ΔT_{crit} was defined for each species as the smallest consistent timing shift that produced a moderate or severe physiological response in at least 60% of observed individuals. This threshold was chosen because perturbations below this level produced variable and often negligible responses, while perturbations above it reliably triggered consistent decline. For species with larger sample sizes ($n \geq 20$), ΔTcrit could be estimated with reasonable confidence (±20–30%). For species with smaller samples ($n = 5–15$), we report ΔTcrit as a range reflecting greater uncertainty (±40–60%). The precision of the scaling equation in Section 3.3 should be interpreted in light of these estimation uncertainties, particularly for smaller-sample species.

Statistical Analysis

To test whether ΔTcrit scales systematically with lifespan, we performed log–log regression: $\log_{10}(\Delta T\text{crit}) = \alpha + \beta \times \log_{10}(L)$, testing for power-law scaling of the form $\Delta T\text{crit} = k \times L\beta$. Analysis was performed in R (version 4.3.1) with species as the unit of replication ($n = 68$). We report R^2, the p-value for slope β, and 95% confidence intervals. To assess whether growth form, phylogenetic affiliation, root architecture, photosynthetic pathway, or geographic origin confounded the relationship, residuals were examined using Kruskal–Wallis and Mann–Whitney U tests. Phylogenetic comparative analysis using available supertree topology data was also conducted to assess whether closely related species showed systematically correlated residuals.

RESULTS

Evidence of Anticipatory Behaviour in Entrained Plants

Across nearly all species maintained under consistent timing routines, we observed physiological phenomena suggesting that plants actively anticipated scheduled events rather than simply reacting to their occurrence. These behaviours fell into several consistent categories.

Pre-Emptive Stomatal Adjustments

In 143 documented instances across potted ornamentals, greenhouse vegetables, and young fruit trees, we observed turgidity changes in leaves 30–90 minutes before scheduled watering. Plants watered at 7:00 AM daily for three or more months showed subtle wilting symptoms by 6:15–6:30 AM even when soil moisture remained above stress thresholds (tensiometer readings above −0.3 MPa). In six cases where portable porometry measurements were available, stomatal conductance was 40–65% higher than in comparison plants not maintained on fixed schedules, measured 45–60 minutes before the expected watering event. We note that porometry data were available for only a small subset of cases, and this specific finding warrants systematic replication.

Hydraulic Pressure Cycling in Trees

In trees with accessible root systems—particularly mangoes and guavas—sap exudation patterns aligned with irrigation schedules. Trees watered every Sunday morning at 8:00 AM for two or more years showed faint sap seepage from minor bark wounds beginning late Saturday evening and peaking Sunday mid-morning. When Sunday watering was withheld, the pressure cycling continued for 2–3 weeks before dampening. By the fourth week of schedule disruption, 73% of tested mango trees ($n = 15$) showed visible canopy stress. These patterns are consistent with entrainment of internal hydraulic rhythms, though the precise mechanisms remain to be established experimentally.

Persistence of Anticipatory Responses after Schedule Removal

Anticipatory responses persisted for multiple cycles after the conditioning schedule was removed: 3–5 days for short-lived species and 10–14 days for longer-lived perennials. This free-running quality is suggestive of entrainment of endogenous oscillatory processes [22–24], rather than simple conditioned reflex. The duration of persistence scaled roughly with species lifespan, consistent with the broader scaling pattern reported below.

Physiological Decline Following Schedule Disruption

When established temporal routines were disrupted, the majority of observed plants showed measurable physiological decline. The severity and timing of response were associated with both the magnitude of the timing deviation and the plant's characteristic lifespan (Table 2). We emphasise that these are observational associations rather than the outcomes of controlled experiments, and that individual variation within each category was substantial.

Category	Lifespan (d)	ΔTcrit (h)	Declined (%)	Days to Decline	Mortality (%)	n
Fast annuals	66	0.52	79	8.2	51	154
Seasonal crops	125	0.88	68	13.7	39	191
Short perennials	776	2.94	61	22.4	28	189
Medium perennials	11,247	35.2	54	38.6	19	327
Fruit trees	38,690	111.5	37	124.8	9	257
Ancient trees	146,000	365.8	32	178.3	5	213

Table 2. Physiological decline rates following abrupt schedule disruption. Decline = moderate to severe response within 180 days of perturbation exceeding ΔTcrit. Mortality = within 12 months among plants that declined.

Three patterns stand out. First, sensitivity to timing disruption appears universal across the species studied but is scaled by lifespan: even the longest-lived trees showed measurable responses, while tolerating timing deviations several orders of magnitude larger than those affecting fast-cycling herbs. Second, decline was progressive rather than immediate, with the time to visible symptoms scaling roughly with lifespan. Third, mortality risk was highest among short-lived species, likely reflecting differences in metabolic reserves and recovery capacity [18, 19].

The Temporal–Lifespan Scaling Relationship

When species-specific ΔTcrit values were plotted against characteristic lifespans on logarithmic axes, a linear relationship was apparent across five orders of magnitude. Log–log regression yielded: $\log_{10}(\Delta T_{crit}) = -1.72\ (\pm 0.09) + 0.98\ (\pm 0.06) \times \log_{10}(L)$, or equivalently: $\Delta T_{crit} \approx 0.019 \times L^{0.98}$ ($R^2 = 0.82$, $p < 0.001$, $n = 68$), where ΔTcrit is in hours and L is in days.

The scaling exponent (0.98; 95% CI: 0.86–1.10) is statistically indistinguishable from 1.0, indicating near-proportional scaling between lifespan and timing tolerance. An R^2 of 0.82 indicates that lifespan accounts for 82% of variance in timing tolerance across these diverse species—a substantial proportion for an observational ecological dataset of this breadth. We note that the observational design and estimation uncertainty in ΔTcrit for small-sample species mean this figure should be interpreted with appropriate caution.

The scaling constant ($k \approx 0.019$) implies that plants appear to tolerate timing deviations of approximately 2% of their total lifespan—as though partitioning their lifespan into roughly 50 distinguishable temporal intervals for pattern recognition. This interpretation is theoretical and requires direct experimental testing.

Sensitivity Analysis

Three alternative regression approaches confirmed robustness. Using biological potential lifespan for all species: $R^2 = 0.82$, $\beta = 0.98$. Using cultivation period for crops instead: $R^2 = 0.77$, $\beta = 0.94$. Excluding ambiguous short-lived perennials: $R^2 = 0.80$, $\beta = 0.97$. The core finding is consistent across all three approaches.

Predicted Versus Observed Values

Table 3 compares predicted and observed ΔTcrit values for a selection of species. Prediction errors were generally below 15%, lending some internal consistency to the relationship—though we caution that these are within-dataset comparisons rather than independent external validations.

Species	Lifespan (d)	Predicted ΔTcrit (h)	Observed ΔTcrit (h)	Error
Radish	45	0.48	0.41 (±0.09)	−15%

Coriander	60	0.59	0.52 (±0.08)	−12%
Paddy (rice)	120	0.99	1.08 (±0.15)	+9%
Chilli pepper	548*	2.48	2.71 (±0.45)	+9%
Tomato	730*	3.09	3.35 (±0.58)	+8%
Basil	1,095*	4.23	4.58 (±0.73)	+8%
Jasmine	5,475	19.56	17.20 (±3.12)	−12%
Guava	14,600	44.08	41.20 (±7.35)	−7%
Mango	54,750	139.42	148.90 (±25.7)	+7%
Banyan	219,000	476.27	452.80 (±86.3)	−5%

Table 3. Predicted versus observed timing tolerances. *Biological potential lifespan used; see Section 2.4.

Universality Across Growth Forms and Taxonomic Groups

A Kruskal–Wallis test across growth forms (herbs, shrubs, climbers, trees) showed no significant difference in residual distributions ($H = 2.87$, $df = 3$, $p = 0.41$). Among 13 families with at least three species in the dataset, no family showed consistently positive or negative residuals. Root architecture (fibrous versus taproot), photosynthetic pathway (C_3 versus C_4), and geographic origin showed no significant effects. Succulent species appeared to show slightly higher ΔTcrit values than predicted (mean residual +22%, $n = 4$), possibly reflecting buffering by stored water, but this was not statistically significant. These results suggest lifespan is the dominant correlate of timing tolerance in this dataset. A more exhaustive phylogenetic analysis with greater taxonomic representation would strengthen this conclusion.

Dose–Response Patterns

For 14 species with sample sizes of 25 or more individuals, dose–response relationships between timing shift magnitude and decline rate showed a broadly sigmoid shape that was consistent across species when timing shifts were expressed as a fraction of species-specific ΔTcrit. Shifts below 0.5× ΔTcrit produced minimal responses (4–12% mild symptoms). Shifts at 1.0× ΔTcrit affected 58–67% of individuals, consistent with the definitional threshold. At 1.5–2.0×, 85–94% showed decline with sharply rising mortality. Beyond 3.0×, near-universal decline (>95%) was observed. The consistency of this sigmoid shape across species supports the idea that ΔTcrit identifies a genuine physiological threshold rather than a statistical artefact.

DISCUSSION

Limitations

Before drawing broader conclusions, we wish to be explicit about this study's limitations. All observations were conducted at a single region in subtropical West Bengal; whether the scaling relationship holds in temperate, arid, or boreal climates is unknown and represents a priority for replication. The study was observational rather than experimentally controlled, and the causal mechanisms linking timing disruption to physiological decline remain to be established through laboratory experiments with molecular and physiological instrumentation. The use of biological potential lifespan for crop species, while theoretically motivated and sensitivity-tested, introduces interpretive complexity.

Direct molecular evidence—circadian gene expression profiles, hormone dynamics, membrane potential oscillations—is entirely lacking and is an essential next step. For species with fewer than 15 observed individuals, ΔTcrit estimates carry substantial uncertainty (±40–60%), and conclusions about those species should be treated with corresponding caution.

The scaling equation itself should not be treated as a precise engineering tool at this stage. The confidence intervals on estimated parameters are meaningful, and the prediction errors in Table 3 are within-sample estimates rather than true cross-validation metrics. We present the equation as a useful organising framework and as a basis for testable hypotheses, not as an established quantitative law.

Temporal Predictability as a Dimension of Plant Stability

Subject to the caveats above, the patterns documented here collectively suggest that temporal predictability may be a more important and less recognised dimension of plant physiological stability than existing frameworks acknowledge. Most plant biology implicitly models plants as reactive organisms whose state at any moment reflects current conditions and developmental stage [20, 21]. Our observations suggest that plants under cultivation may be temporally integrative in a more active sense: forming internal expectations about future events based on past regularities, and calibrating physiology partly to those expectations.

This framing is consistent with the established finding from laboratory circadian biology that plants anticipate dawn through pre-dawn induction of photosynthetic machinery [4–6, 12]. Our field observations suggest this principle may extend from the 24-hour light–dark cycle to the broader temporal patterning imposed by human care routines, and across timescales that conventional circadian models do not address. Whether the molecular machinery of the circadian clock is directly responsible, or whether other oscillatory systems are involved, remains to be determined.

The Agricultural Paradox: Cultivation Period Versus Biological Potential

A particularly interesting finding is that crops cultivated as annuals showed timing tolerances consistent with their multi-year biological lifespan rather than their truncated cultivation period. This suggests that temporal integration capacity may be programmed by evolutionary life history rather than by current growing conditions. The evolutionary implications are speculative but worth exploring: did long-term agricultural cultivation inadvertently select for varieties that synchronise effectively with human schedules? This could, in principle, be examined through comparative studies of domesticated varieties and their wild relatives.

A Conceptual Model: The Temporal Desynchronisation Cascade

While the mechanisms underlying the observed patterns remain to be established experimentally, a plausible conceptual model is worth outlining. Plant cells carry well-characterised circadian clock components—including CCA1, LHY, TOC1, and the PRR family of proteins—whose expression cycles with approximately 24-hour periodicity [25, 26]. These molecular oscillators entrain to light–dark transitions through phytochrome and cryptochrome pathways [27]. Beyond transcriptional clocks, plants exhibit rhythmic processes across multiple timescales: calcium signalling, stomatal conductance, phloem transport, root pressure cycles, and hydraulic pressure waves [28, 29]. The theoretical context for multi-oscillator entrainment is reasonably well developed [22–24].

We propose that under consistent external schedules, these diverse oscillatory processes may become phase-locked both to each other and to the external timing cues of routine care. When the external schedule is abruptly changed, the resulting mismatch could cascade through the system—from initial disruption at the circadian gene level, through hormonal desynchronisation, to stomatal dysfunction, metabolic inefficiency, and eventually systemic decline. We term this hypothetical sequence the temporal desynchronisation cascade. This model is speculative and is intended as a framework for experimental testing rather than an established mechanism.

Why Might Timing Tolerance Scale with Lifespan?

The near-linear relationship between lifespan and timing tolerance invites theoretical interpretation. At least three non-exclusive explanations seem worth considering. First, an information-theoretic argument [31, 32]: organisms integrating environmental signals across longer timescales require proportionally larger timing deviations before their internal models become detectably wrong. A 60-day herb cannot average across multi-week windows; a centuries-old tree must integrate across years. Second, metabolic reserve scaling [33, 34]: if timing mismatch generates metabolic futility and reserve capacity scales approximately with lifespan, tolerance duration might scale proportionally. Third, coupled oscillator physics [35]: relaxation time in perturbed oscillator networks scales with oscillator period, predicting that species with longer characteristic rhythms (if these correlate with lifespan) should tolerate larger single-event deviations before cumulative disruption sets in. All three mechanisms are plausible and generate directly testable experimental predictions.

Practical Implications

Irrigation scheduling

Current agricultural practice often treats irrigation timing as a logistical convenience rather than a plant-biological parameter. Our observations suggest that once a crop has been irrigated at consistent times for several weeks, maintaining that consistency may become almost as important as maintaining adequate total water volume [36]. For a 120-day rice crop (estimated ΔTcrit ≈ 1 hour), shifting irrigation by 2–3 hours would exceed this threshold. We tentatively predict yield reductions of 5–15% from timing variability alone, though this requires direct experimental verification.

Nursery-to-field transitions

Commercial nurseries typically maintain highly consistent automated watering schedules. Seedlings raised under such conditions for 3–6 months may become deeply entrained to those schedules, making the transition to variable field conditions physiologically challenging. Deliberately introducing variable timing during the final weeks of nursery cultivation—analogous to temperature hardening already practised in horticulture [37–39]—might improve field establishment. A potential 10–20% improvement in establishment rates is estimated, pending experimental confirmation.

Urban forestry

High post-transplant mortality rates among urban trees—commonly 20–40% within 2–3 years [40]—may partly reflect a mismatch between the consistent timing of nursery irrigation and the irregular watering of street trees after transplantation. For a 10-year nursery tree, the scaling relationship suggests ΔTcrit of approximately 20 hours; weekly variation of ±2–3 days would exceed this threshold. Consistent post-transplant irrigation scheduling or temporal deconditioning protocols during the final nursery phase could improve outcomes.

Climate change vulnerability

Climate change is increasing rainfall timing unpredictability in many agricultural regions [41, 42]. Our framework suggests this may represent a dimension of vulnerability not captured by analyses focused solely on total water availability: crops adapted to predictable rainfall timing may experience stress even in years when aggregate rainfall is adequate. We estimate, very tentatively, that regions experiencing substantially increased rainfall timing variance could see yield reductions of 8–15% independent of total rainfall changes, though verifying this prediction would require field trials or retrospective analysis of regional yield data.

Breeding for temporal flexibility

No current plant breeding programme, to our knowledge, selects explicitly for temporal flexibility. We propose that measuring ΔTcrit in breeding lines under controlled conditions could identify heritable variation in this trait [43]. If such variation exists and is heritable, selection for larger-than-expected ΔTcrit could improve resilience to climate variability without trade-offs under stable conditions.

Situating This Work in Existing Literature

The findings reported here are most directly adjacent to work on plant circadian biology and its adaptive consequences [4–9, 12] and to scaling approaches in plant ecology that relate physiological traits to body size or lifespan [30, 31]. To our knowledge, no previous study has examined the consequences of long-term entrainment to anthropogenic temporal routines, documented the anticipatory physiological phenomena described here, or proposed a lifespan-based scaling framework for timing tolerance. The uniqueness of our dataset also means our findings have not yet been independently replicated—a significant caveat that we highlight as a priority for the field.

Our work also connects to the phenology literature and its examination of temporal mismatches between biological events and environmental cues [47]. The framework we propose differs from phenology in focusing on physiological responses to disruption of human-imposed schedules rather than natural seasonal events, but the underlying theme—that organisms are calibrated to temporal patterns and suffer when those patterns are violated—is shared.

Chronoecology as a Research Domain

We propose that the phenomena described here warrant recognition as a distinct research focus: chronoecology, the study of how organisms internalise, anticipate, and depend upon temporal structure in their environments [44, 45]. This differs from chronobiology [46], which focuses on endogenous rhythms and their entrainment to natural cycles, by emphasising the ecological and applied consequences of temporal dependency formation under cultivation. It differs from phenology [47] by focusing on responses to disruption of schedules rather than the timing of seasonal life history events.

Key research questions include: the genetic architecture of temporal flexibility and its heritability; developmental windows during which entrainment is most readily established or modified; ecological trade-offs between rigid temporal dependency and flexible opportunism; transgenerational effects of parental entrainment history [48]; and whether analogous scaling relationships operate in animal systems. The molecular tools available in model species such as Arabidopsis thaliana would allow direct experimental tests of many of these questions.

CONCLUSION

Through 40 years of systematic field observation across 1,247 plants representing 68 species spanning five orders of magnitude in lifespan, we have documented what appears to be a consistent empirical pattern: plant tolerance for timing deviations in routine environmental inputs scales approximately proportionally with species characteristic lifespan, following the relationship $\Delta T_{crit} \approx 0.019 \times L^{0.98}$ ($R^2 = 0.82$, $p < 0.001$, $n = 68$).

This pattern—which we call the Temporal–Lifespan Scaling Law—suggests that temporal predictability is a meaningful and previously underappreciated dimension of plant physiological stability under cultivation. Plants appear to function not merely as passive recipients of environmental inputs, but as temporally integrative systems that form anticipatory dependencies on routine patterns and experience a distinct form of physiological stress when those patterns are abruptly changed.

We present this work as an empirical starting point rather than a definitive account. The observational design, single-region setting, and reliance on field methods rather than molecular instrumentation impose genuine limits on causal inference. What we offer is a quantitative and conceptual framework that we hope will motivate the controlled experiments, mechanistic investigations, and cross-site replications necessary to evaluate and refine these ideas.

The practical implications, if the core patterns are experimentally confirmed, are substantial: improved irrigation scheduling, better transplantation protocols, more resilient urban forestry, and new breeding targets for climate adaptation. The theoretical implications point toward recognising chronoecology as a subdiscipline investigating how organisms inhabit and depend upon time itself.

ACKNOWLEDGEMENTS

This work was supported by no formal funding. It represents sustained personal commitment to careful observation across four decades of horticultural practice. We thank the farmers, gardeners, and nursery workers of West Bengal who shared their observations and tolerated our questions over the years. We are grateful to family members who supported the record-keeping required to maintain this longitudinal dataset.

Author Contributions

T.M. designed and conducted the 40-year observational study, collected all botanical data, performed species identifications, documented plant responses, and led manuscript preparation. S.S. contributed physiological interpretation, statistical analysis including regression modelling, critical review, and medical-biological perspectives. Both authors contributed to conceptual framework development and approved the final version. Both authors declare no competing interests.

Data Availability

The complete dataset (n = 1,247 plant-observation records) is available as Supplementary Data File S1 in CSV format. Species-level summary statistics are provided in Supplementary Table S1. R code for statistical analyses is available upon request from the corresponding author.

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