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A review on extreme weather events and insect pest dynamics

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Abstract

Rising atmospheric variability has reshaped the frequency and intensity of heatwaves, droughts, erratic rainfall and cyclonic storms across agricultural landscapes worldwide, and insect pest populations are responding in ways that defy simple linear projections tied to mean temperature rise alone. Physiological, ecological and modelling evidence to examine how extreme rather than average climatic shifts govern pest establishment, voltinism, dispersal and outbreak severity across cropping systems in temperate, tropical and semi-arid regions. Findings across independent research groups converge on several points and diverge sharply on others. Thermal tolerance breadth, developmental plasticity and natural enemy disruption emerge as recurring determinants of whether a pest population benefits or collapses under episodic climatic stress, yet predictions built from controlled laboratory assays frequently fail to anticipate field-level outcomes shaped by microclimate buffering, host plant physiology and trophic cascade effects. Attention is given to the asymmetry between gradual warming trends, which many pest species appear able to track through range shifts and phenological adjustment, and abrupt weather anomalies, which impose thresholds that override adaptive capacity within a single generation. Persistent gaps in long-term field validation, taxonomic bias toward a handful of well-studied lepidopteran and hemipteran pests, and the near absence of multi-stressor experimental designs are identified as limiting the predictive reliability of current pest forecasting frameworks under an increasingly volatile climate regime.

Keywords: Climate variability, insect pest outbreaks, thermal tolerance, extreme weather, phenological mismatch, agroecosystem resilience

Introduction

Insect pests have always tracked climatic variation, moving with seasons, retreating during cold snaps and multiplying rapidly whenever conditions align with their physiological optima. What has changed over the past three decades is not simply the direction of temperature trends but the shape of the distribution around them. Heatwaves that once occurred once in a generation now recur within a farmer's working lifetime, monsoon onset dates across South Asia have become erratic by weeks rather than days, and cyclonic systems in several ocean basins have intensified in both frequency and peak wind speed (IPCC, 2021) ^[9]. Deutsch *et al.*, (2018) ^[6] demonstrated that even modest global mean warming translates into disproportionate increases in crop losses to insect pests in temperate grain producing regions, largely because metabolic scaling and reduced winter mortality push populations past thresholds that summer heat alone cannot explain. This finding reoriented much of the subsequent literature away from a narrow focus on mean annual temperature and toward the variance structure of weather itself.

Walther *et al.*, (2002) ^[21] had earlier catalogued a broad suite of ecological responses to recent climatic change, ranging from phenological advancement to poleward range extension, and insect herbivores featured prominently among the taxa showing the fastest measurable shifts. Parmesan and Yohe (2003) ^[14] extended this by quantifying a globally coherent fingerprint across thousands of species records, a pattern that agricultural entomologists have since used as a baseline against which to judge whether pest range changes reflect genuine climatic forcing or confound with land use change and pesticide selection pressure. The difficulty, as several authors have pointed out, is that averaged climatic trends and extreme weather anomalies do not act on insect populations through the same mechanism. Gradual warming permits developmental

and behavioural tracking across generations, whereas a single heatwave, flash flood or unseasonal frost can impose an acute mortality event that no amount of prior adaptation fully buffers against (Ma *et al.*, 2021) ^[12].

Bale *et al.*, (2002) ^[2] framed this distinction early in the herbivory literature, cautioning that laboratory-derived thermal performance curves built around gradual temperature ramps routinely overestimate a population's resilience to episodic extremes encountered under field conditions. Vasseur *et al.*, (2014) ^[20] later formalised this concern mathematically, showing that increased temperature variance around an unchanged mean poses a materially greater extinction risk to ectotherm populations than warming of the mean itself, a result with direct implications for how pest risk models ought to be parameterised. This review draws together the physiological, phenological and ecological strands of that literature to ask a deceptively simple question that the field has not yet answered with consensus, namely whether extreme weather events on balance suppress or amplify insect pest pressure on global agriculture, and under what conditions each outcome should be expected.

Thermal Extremes and the Limits of Insect Physiological Tolerance

Insect body temperature tracks ambient conditions closely enough that thermal performance curves have become the default currency for predicting pest response to warming. Yet the curve itself is asymmetric, rising gradually from a lower developmental threshold to an optimum and then falling sharply toward a critical thermal maximum, and it is this steep upper slope that extreme heat events exploit. Ma *et al.*, (2021) ^[12] reviewed the physiological mechanisms underlying survival at supra-optimal temperatures and concluded that heat shock protein induction, cuticular water conservation and behavioural avoidance together determine whether a population merely loses fitness during a heatwave or suffers outright collapse. What emerges from this literature is a picture considerably more nuanced than the notion that warming simply helps pests. Larval stages of many lepidopteran pests, still confined to a feeding site on the host plant, cannot escape a heatwave the way a mobile adult can, and mortality is concentrated disproportionately in these immobile stages.

Colinet *et al.*, (2015) ^[5] pushed the argument further by showing that constant-temperature laboratory assays, the standard tool for building thermal performance curves, systematically misrepresent how insects experience fluctuating field temperatures. Repeated brief exposures above the critical thermal maximum, interspersed with recovery periods, produce cumulative physiological damage that a single continuous exposure of the same total duration does not, and most published thermal tolerance data are still generated under the simpler continuous-exposure protocol. This methodological mismatch matters because it means that risk assessments built from existing thermal tolerance databases may understate mortality during real heatwave events, which are inherently pulsed rather than continuous.

Sentis *et al.*, (2013) ^[17] added a trophic dimension by simulating heatwaves within an experimental plant-herbivore-predator chain and found that the herbivore population, aphids in this case, crashed sharply during the simulated event but that predator populations crashed further and recovered more slowly. The net effect several weeks after the heatwave was a herbivore population released from top-down control, a counterintuitive outcome given the immediate suppression observed during the event itself. This result illustrates why single-species thermal

tolerance data, however well replicated, cannot on their own predict community-level or agronomically relevant outcomes. Deutsch *et al.*, (2018) ^[6] reached a related conclusion from a different angle, modelling metabolic rate increases under warming and projecting substantially higher pest-driven yield losses for staple cereals even without invoking any single catastrophic heat event, purely from the cumulative effect of faster development and higher overwinter survival.

Taken together, this body of work suggests that thermal extremes act on insect pests through at least three distinguishable pathways operating on different timescales, namely acute mortality during the event itself, delayed disruption of natural enemy populations that recover more slowly than the pest, and chronic metabolic acceleration from a warmer background climate that raises baseline population growth rates between extreme events. Disentangling which pathway dominates in a given cropping system remains an open empirical challenge, and the answer appears to depend heavily on the relative thermal sensitivity of the pest compared with its principal natural enemies rather than on any fixed rule applicable across taxa.

Precipitation Extremes, Drought Stress and Outbreak Triggers

Where thermal extremes act primarily through direct physiological stress on the insect, precipitation extremes more often act indirectly, mediated through host plant physiology, soil moisture and microhabitat conditions. Netherer and Schopf (2010) ^[13] documented this pathway in detail for European conifer forests, where prolonged drought reduces resin flow and defensive chemistry in host trees, allowing bark beetle populations that would otherwise be held below outbreak thresholds by tree defences to erupt into landscape-scale infestations. The trigger in these systems is not heat tolerance in the beetle at all but the collapse of host resistance under water stress, a mechanism that would be entirely missed by a thermal-tolerance-only framework.

Jactel *et al.*, (2019) ^[10] reviewed this literature critically and cautioned against treating the drought-outbreak link as a universal rule. Some forest pest species respond to drought-weakened hosts exactly as the bark beetle model predicts, while others show no clear relationship or even a negative one, particularly where drought simultaneously reduces the nutritional quality of foliage below a threshold the insect itself can tolerate. Their synthesis argued that host plant identity and the specific feeding guild of the pest, whether phloem-feeding, foliage-chewing or sap-sucking, determine which direction the drought effect runs, and that generalising from conifer bark beetle systems to agricultural pests in annual cropping systems is not straightforward.

Rosenzweig *et al.*, (2001) ^[16] took a broader food-security perspective, arguing that extreme precipitation events, both drought and flood, alter pest and pathogen pressure on staple crops through pathways that extend well beyond direct insect physiology, including changes in planting date, crop stress susceptibility and the synchrony between pest emergence and vulnerable crop growth stages. Their analysis, written before the more recent wave of mechanistic thermal biology studies, remains relevant precisely because it locates the agronomic consequence of extreme weather in the interaction between crop stress and pest pressure rather than in either factor alone. Robinet and Roques (2010) ^[15] offered a complementary observation from soil-dwelling and subterranean insect groups, noting that termite and root-feeding pest activity tracks soil

moisture extremes more directly than air temperature extremes, since mound and burrow microclimates buffer thermal variation far more effectively than they buffer moisture deficits.

Battisti and Larsson (2015) ^[3], reviewing range dynamics of the pine processionary moth, provided one of the clearer cases where a single climatic variable, in this instance winter cold severity rather than either summer heat or precipitation, dominates the outbreak and range-expansion signal. The comparison across these systems suggests that no single extreme weather category, whether thermal, precipitation-driven or a combination, can be assumed a priori to be the dominant driver for a given pest, and that mechanistic studies identifying the specific limiting factor for each pest-crop system remain more useful than broad correlational climate-pest models.

Phenological Decoupling and Trophic Mismatch Under Climatic Variability

A recurring theme across the climate-insect literature is that species do not all shift their timing at the same rate, and this differential responsiveness generates mismatch between interacting trophic levels even when each species individually tracks climate change reasonably well on its own terms. Thackeray *et al.*, (2016) ^[19] quantified phenological sensitivity across a very large multi-taxon dataset spanning primary producers, herbivores and predators, and found that lower trophic levels, including many herbivorous insects, tend to advance their spring timing faster than the plant or predator species with which they interact. For pest management this asymmetry cuts both ways. In some documented cases pest emergence has advanced ahead of natural enemy activity, providing a temporary window of reduced biological control, while in others host plant phenology has advanced faster than pest emergence, shortening the period during which a vulnerable crop growth stage coincides with peak pest pressure.

Walther *et al.*, (2002) ^[21] had already flagged phenological advancement as one of the most consistently observed ecological fingerprints of climatic change, and subsequent work has generally confirmed the direction of the trend while revealing substantial variability in its magnitude across taxa and regions. Parmesan and Yohe (2003) ^[14] situated insect phenological shifts within this wider pattern, noting that the rate of advancement correlates with local warming rate more closely than with any inherent biological trait of the species concerned, which implies that the degree of trophic mismatch a given cropping system experiences will itself vary regionally according to local climatic trends rather than following a single global rule.

Extreme events complicate this picture further because they can override gradual phenological trends within a single season. An unseasonably warm spring followed by a sharp late frost, for instance, can advance pest emergence and then impose acute mortality on the same cohort, producing outcomes that neither a warming-trend model nor a frost-frequency model captures in isolation. Sentis *et al.*, (2013) ^[17] demonstrated an analogous compounding effect at the trophic level, where a heatwave disrupted both herbivore and predator populations but on different timescales, leaving a temporary window of reduced top-down control that a phenology-only framework would not have anticipated. The practical implication for pest forecasting is that phenological models calibrated purely against long-term mean climatic trends are unlikely to capture the additional variance introduced by episodic extremes layered on top of that trend, and several authors have argued that this gap constitutes one of the more consequential blind spots in current pest

advisory systems.

Conflicting Evidence

Perhaps the least settled question in this literature is whether extreme weather, on net, favours or suppresses insect pest populations, and the disagreement is not merely a matter of insufficient data but appears to reflect genuine underlying heterogeneity across systems. Lehmann *et al.*, (2020) ^[11] synthesised evidence across multiple pest taxa and explicitly rejected the notion of a uniform directional response to warming, reporting that outcomes ranged from strongly positive population responses in some pest-crop combinations to clearly negative responses in others, with the direction depending on interacting factors including voltinism potential, overwintering strategy and natural enemy community composition. This heterogeneity sits uncomfortably alongside the more widely cited projection from Deutsch *et al.*, (2018) ^[6] of broadly increased pest pressure under warming, and reconciling the two requires recognising that the Deutsch projection was built primarily around temperate cereal systems where overwinter mortality reduction is a particularly strong lever, a mechanism that does not apply with the same force in already-warm tropical systems.

Skendžić *et al.*, (2021) ^[18] reviewed agricultural pest responses more broadly and reached a position closer to Lehmann *et al.*, (2020) ^[11] than to a simple universal-increase narrative, emphasising that range-shifting pests moving into newly favourable climatic zones can experience strong population growth in the invaded range while simultaneously experiencing decline or extirpation at the historically warm edge of their existing range, so that a single species can be simultaneously a winner and a loser depending on which part of its distribution is examined. Bebbier *et al.*, (2013) ^[4] provided independent empirical support for the range-shift component of this pattern, documenting a measurable poleward movement of crop pest and pathogen distributions since the 1960s that tracks warming isotherms, though their analysis could not by itself resolve whether population densities within the shifting range were also increasing or whether the shift represented redistribution of a roughly constant total population.

Diffenbaugh *et al.*, (2008) ^[7] approached the same question from a regional agronomic angle, projecting how warming would alter the geographic overlap between a major maize pest and its host crop across the United States Corn Belt, and found that the projected changes in pest-crop synchrony varied considerably across sub-regions even within a single country and a single pest-crop system. This kind of fine-grained heterogeneity, replicated across multiple independent studies using different methods, argues against treating extreme weather and insect pest dynamics as a topic amenable to a single global generalisation. The disagreement in the literature is therefore less a matter of conflicting data quality and more a reflection of genuinely conditional outcomes that depend on the specific pest, crop, region and type of extreme event under consideration.

Gaps and Limitations

Several structural limitations recur across the literature reviewed here and constrain how confidently any of these findings can be extrapolated to future climatic conditions. The first is a pronounced taxonomic bias. Andrew *et al.*, (2013) ^[1] conducted a systematic assessment of how insect climate-response studies are designed and found heavy over-representation of a small number of well-studied lepidopteran, hemipteran and orthopteran pest species, with entire feeding guilds and

taxonomic orders remaining almost unstudied in the context of extreme weather response. This bias limits the ability of the field to generalise findings from a handful of intensively studied pests, such as those summarised in the tables of this review, to the far larger set of economically important pests for which comparable data simply does not exist.

A second limitation concerns the mismatch between laboratory and field conditions already noted in relation to thermal tolerance. Colinet *et al.*, (2015) ^[5] argued that this gap is not merely a matter of insufficient replication but reflects a fundamental design problem, since most experimental protocols were established decades ago around constant-temperature exposure and have not been systematically updated to reflect the pulsed, compound nature of real extreme weather events. Multi-stressor experimental designs, combining heat with drought or with altered humidity, remain comparatively rare, and Jactel *et al.*, (2019) ^[10] specifically identified the near absence of such combined-stressor studies in forest pest research as a major constraint on translating single-factor laboratory findings into field-relevant predictions.

A third limitation concerns temporal scale. Most pest response studies, whether observational or experimental, are conducted over one to a few seasons, whereas the outbreak dynamics that matter most economically often unfold over multi-year cycles

involving delayed natural enemy responses, host plant resistance induction and soil or forest stand-level legacy effects. Netherer and Schopf (2010) ^[13] noted this explicitly in the context of bark beetle outbreaks, where the lag between a drought event and peak outbreak severity can extend across several years, a timescale that few funded research programmes are structured to capture. Harvey *et al.*, (2023) ^[8] raised a related concern at a broader scale, arguing that the cumulative, insufficiently studied effects of climatic volatility on insect populations generally, pests included, are likely to be systematically underestimated by research programmes oriented toward single-event, short-duration studies rather than long-term population trajectories.

Finally, most predictive models in this literature remain correlative rather than mechanistic at the population level, even where the underlying physiological data are mechanistic. Vasseur *et al.*, (2014) ^[20] demonstrated the value of a more mechanistic, variance-explicit modelling approach, but such approaches have not yet been widely incorporated into applied pest forecasting systems used by extension services, which in most regions still rely on degree-day accumulation models built around mean seasonal temperature trends rather than on the variance-sensitive frameworks that the physiological literature increasingly supports.

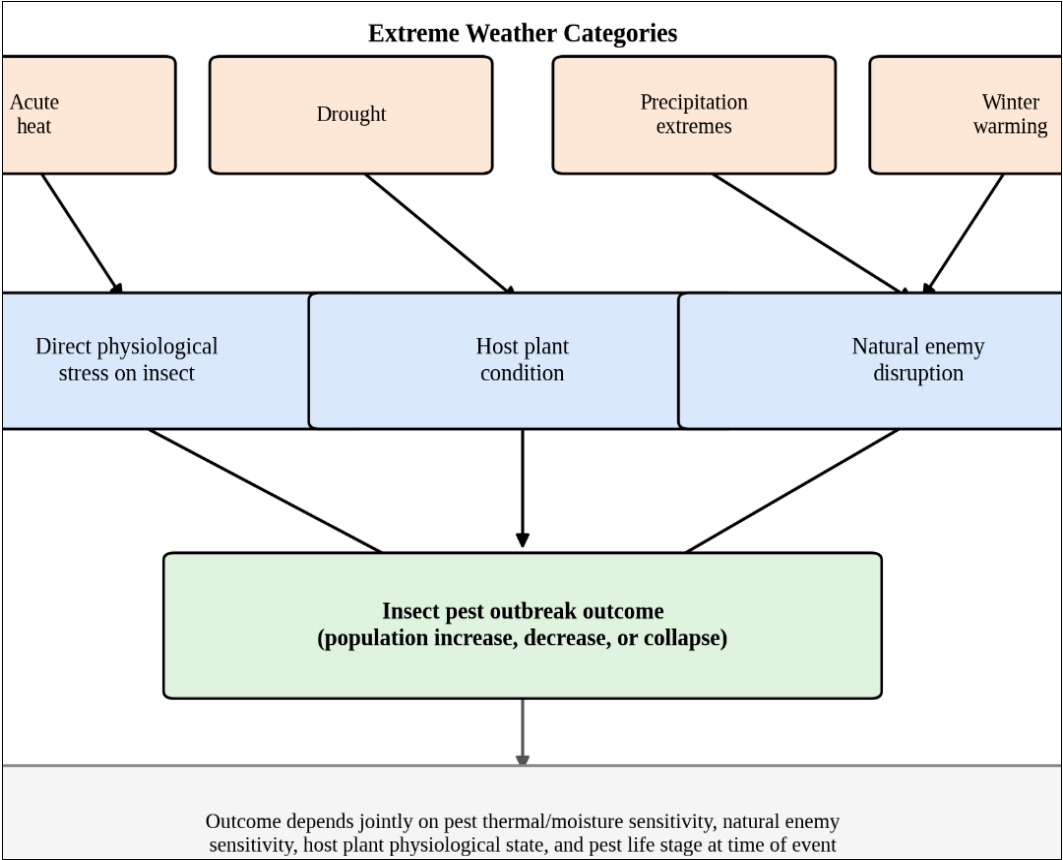


Fig 1: Conceptual pathway linking extreme weather categories to insect pest outbreak outcomes

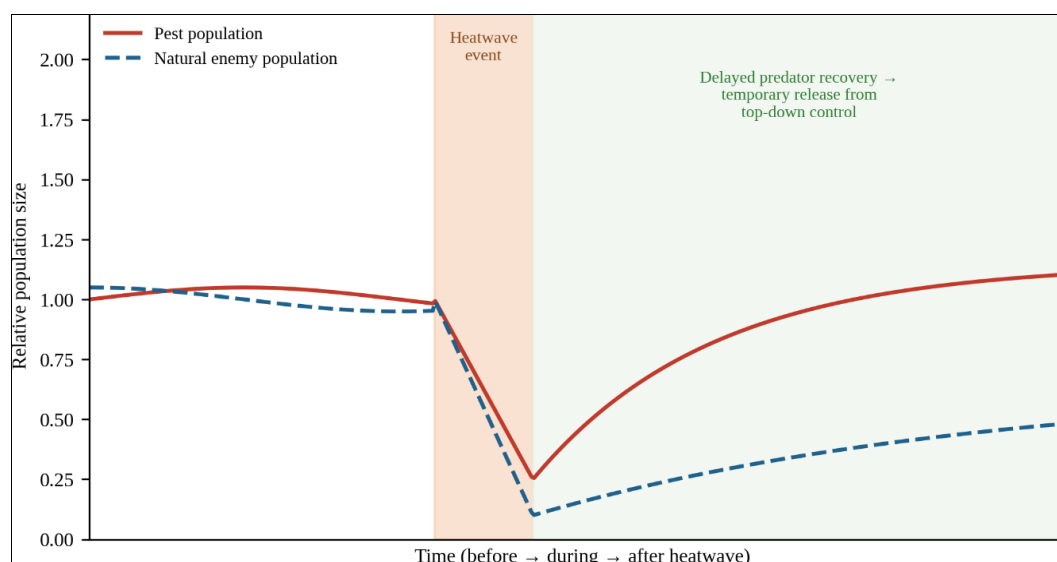


Fig 2: Schematic comparison of population trajectories for a representative pest and its principal natural enemy before, during and after a simulated heatwave event, illustrating the differential recovery lag.

Table 1: Comparative Thermal Tolerance Patterns of Major Insect Pest Groups Under Extreme Heat

Insect Order	Representative Pest Taxa	General Heat-Tolerance Range	Documented Response Pattern Under Extreme Heat	References
Orthoptera (locusts, grasshoppers)	<i>Schistocerca gregaria</i> , <i>Locusta migratoria</i>	Upper critical limits generally among the highest recorded for pest insects, often tolerating brief exposure well above 45 degrees C	Behavioural thermoregulation (basking, shade-seeking) buffers acute heat; rainfall-driven breeding pulses matter more than heat tolerance per se	Ma <i>et al.</i> , (2021) ^[12] ; IPCC (2021) ^[9]
Lepidoptera (bollworms, borers, armyworms)	<i>Helicoverpa armigera</i> , <i>Spodoptera frugiperda</i>	Moderate tolerance with strong life-stage dependence; larvae markedly more heat-sensitive than adults	Heatwaves during larval instars increase mortality and shorten developmental windows, but surviving cohorts show compensatory voltinism gains later in season	Deutsch <i>et al.</i> , (2018) ^[6] ; Ma <i>et al.</i> , (2021) ^[12]
Hemiptera (aphids, whiteflies, planthoppers)	<i>Myzus persicae</i> , <i>Bemisia tabaci</i>	Comparatively narrow thermal safety margin; performance often declines sharply beyond 35 to 38 degrees C	Acute heatwaves can trigger rapid population collapse followed by rebound once natural enemies are also suppressed	Sentis <i>et al.</i> , (2013) ^[17] ; Bale <i>et al.</i> , (2002) ^[2]
Coleoptera (bark and wood borers)	<i>Ips typographus</i> , <i>Dendroctonus</i> spp.	Broad tolerance combined with strong dependence on host tree water status rather than direct thermal limits	Drought-weakened hosts, not heat alone, are the principal trigger for outbreak-scale population growth	Netherer and Schopf (2010) ^[13] ; Jactel <i>et al.</i> , (2019) ^[10]
Diptera (fruit flies, gall midges)	<i>Bactrocera dorsalis</i> , <i>Orseolia oryzae</i>	Moderate tolerance with pronounced humidity dependence	Combined heat and low-humidity extremes reduce adult longevity and oviposition success more than heat alone	Ma <i>et al.</i> , (2021) ^[12] ; Skendžić <i>et al.</i> , (2021) ^[18]
Thysanoptera (thrips)	<i>Thrips tabaci</i> , <i>Frankliniella occidentalis</i>	High developmental plasticity across a wide temperature band	Short generation time allows rapid numerical recovery after heat-related mortality events	Bale <i>et al.</i> , (2002) ^[2] ; Colinet <i>et al.</i> , (2015) ^[5]
Acari (mites, treated alongside insect pests in most agronomic literature)	<i>Tetranychus urticae</i>	Very high upper thermal limits relative to body size	Outbreaks frequently intensify during hot, dry spells when fungal antagonists of mites are simultaneously suppressed	Skendžić <i>et al.</i> , (2021) ^[18]
Isoptera (termites)	<i>Odontotermes</i> spp.	Buffered thermal exposure due to subterranean and mound microclimate regulation	Colony-level activity tracks soil moisture extremes more closely than ambient air temperature extremes	Robinet and Roques (2010) ^[15]
Hymenoptera (sawflies and related defoliators)	<i>Neodiprion sertifer</i>	Cold-limited rather than heat-limited in temperate systems	Warmer, less severe winters raise overwintering survival more than summer heat extremes affect adult performance	Battisti and Larsson (2015) ^[3]
Lepidoptera (forest defoliators)	<i>Thaumetopoea pityocampa</i>	Winter cold tolerance is the principal historical range constraint, not summer heat tolerance	Milder winter extremes, rather than summer heatwaves, have been the dominant driver of documented range expansion	Battisti and Larsson (2015) ^[3] ; Netherer and Schopf (2010) ^[13]

Table 2: Documented Insect Pest Responses to Specific Categories of Extreme Weather Across Regions

Extreme Weather Category	Region	Pest Group Affected	Documented Population or Range Response	References
Winter warming extremes (reduced frost severity)	European and Mediterranean forests	Pine processionary moth	Sustained poleward and altitudinal range expansion tracking reduced winter mortality thresholds	Battisti and Larsson (2015) ^[3] ; Netherer and Schopf (2010) ^[13]
Summer heatwaves	Temperate agroecosystems (Europe, North America)	Aphid-parasitoid-plant food chains	Short-term aphid population crashes followed by disrupted top-down control once parasitoids were also affected	Sentis <i>et al.</i> , (2013) ^[17]
Prolonged drought	Central European conifer forests	Bark beetle complex	Outbreak-scale population growth linked to drought-weakened host defence rather than temperature extremes alone	Netherer and Schopf (2010) ^[13] ; Jactel <i>et al.</i> , (2019) ^[10]
Warming mean and increased thermal variance combined	Global grain-producing regions (temperate belt)	Cereal and stored-grain pests broadly	Disproportionate projected increase in crop loss attributable to metabolic scaling and reduced overwinter mortality	Deutsch <i>et al.</i> , (2018) ^[6]
Poleward climatic shift in growing-season conditions	Global cropland (multi-crop analysis)	Diverse crop pest and pathogen taxa	Measurable poleward shift in realised pest distributions tracking warming isotherms since the 1960s	Bebber <i>et al.</i> , (2013) ^[4]
Increased inter-annual temperature variance (not mean shift)	Marine and terrestrial ectotherm systems (general)	Ectotherm populations broadly, insects included	Elevated extinction and population-crash risk under variance increase exceeding the risk from mean warming of equivalent magnitude	Vasseur <i>et al.</i> , (2014) ^[20]
Altered monsoon timing and intensity	South and Southeast Asian rice systems	Planthoppers and stem borers	Outbreak timing decoupled from historical crop-stage windows, complicating economic threshold-based management	Skendžić <i>et al.</i> , (2021) ^[18] ; Rosenzweig <i>et al.</i> , (2001) ^[16]
Compound heat and humidity extremes	Sub-Saharan and South Asian cropping systems	Fruit flies and gall midges	Reduced adult longevity and oviposition under combined stress relative to either stressor applied singly	Ma <i>et al.</i> , (2021) ^[12]
Advancing spring phenology	Northern temperate ecosystems (multi-taxon)	Herbivorous insects across multiple orders	Widespread but taxon-specific advancement of emergence and activity timing relative to host plant and predator phenology	Thackeray <i>et al.</i> , (2016) ^[19] ; Parmesan and Yohe (2003) ^[14]
General climatic destabilisation (synthesis across events)	Global, cross-biome	Insect fauna broadly, agricultural pests included	Net direction of change (increase versus decrease in pest pressure) found to be system- and taxon-dependent rather than uniform	Lehmann <i>et al.</i> , (2020) ^[11] ; Jactel <i>et al.</i> , (2019) ^[10]

Conclusion

Extreme weather does not exert a single, predictable effect on insect pest populations, and the search for one unifying rule is probably misdirected. What the accumulated evidence supports instead is a conditional framework in which the outcome of any given heatwave, drought, flood or storm depends jointly on the thermal and moisture sensitivity of the pest itself, the sensitivity of its principal natural enemies, the physiological state of the host plant, and the specific life stage exposed at the moment the event occurs. Gradual warming and episodic extremes act through partly overlapping but distinguishable mechanisms, and treating them interchangeably in forecasting models risks understating the acute risks that extremes pose even in systems where mean climatic trends appear, on the surface, moderate. The clearest path forward lies not in a search for a single global pest response coefficient but in system-specific, mechanistically grounded models that explicitly separate the contribution of variance from the contribution of the mean, that incorporate natural enemy dynamics alongside pest dynamics, and that are validated against multi-year field outcomes rather than single-season laboratory assays. Pest management institutions that continue to plan around historical mean-climate baselines will find their advisories increasingly out of step with a climatic regime in which the extremes, not the averages, are doing most of the ecological work.

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