CLIMATE CHANGE RESHAPES RANGE LIMITS, PHENOLOGICAL SYNCHRONY, AND ECONOMIC THRESHOLDS OF COCOA MIRIDS IN WEST AFRICAN AGROFORESTRY SYSTEMS

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ABSTRACT
Climate change is rearranging the spatial and temporal structure of pest pressure of perennial agroforestry systems. More than 70 percent of the global cocoa is produced in West Africa, with the mirid bugs (Sahlbergella singularis Haglund and Distantiella theobroma Distant) being the main biotic factor limiting production stability. However, the dynamics of pest phenology and economic thresholds due to climate warming are unknown. We combined 15 years of climatic data across cocoa-producing regions representing a north–south climatic gradient with longitudinal field surveillance, mechanistic phenological modelling, and recalibrated economic injury thresholds to determine how climate change alters cocoa mirid distribution, seasonal synchrony, outbreak risk, and intervention timing in West African agroforestry systems. Peak mirid abundance had improved with the increase in minimum night temperatures (+1.2°C) by 18-24 days and an increase in latitude northwards (87 km) corresponding to the climatic suitability envelope in 2008. The phenological theory of temperature attributed 71 percent of the variation in pest-crop intersection ($R^2 = 0.71$), in which there is increased synchrony between peak feeding and cocoa cherelle increase. Climate-adjusted density–damage regression models revealed that conventional economic injury thresholds underestimated projected yield losses associated with Sahlbergella singularis infestations by 32% across West African cocoa agroforestry systems. Our results indicate that climate warming is not only causing a rise in pest abundance but also redefining geographical range boundaries, squeezing seasonal pest-crop interactions, and disrupting most of the set economic decision rules. These findings make the cocoa mirid system an example for studying how climate change alters pest risk and management thresholds in perennial agricultural systems worldwide.

Keywords: Climate Warming, Phenological Synchrony, Geographic Range Shift, Economic Injury Level, Cocoa Agroforestry, Insect Pest Dynamics, Climate-Adaptive Management

INTRODUCTION

Perennial agroforestry has been considered a resilient production terrain because it subsidises climatic fluctuations, facilitates biodiversity, and supports rural lives (Igbatayo, 2023). Meanwhile, their ecological stability has to do with highly coupled trophic relationships that are substantially sensitive to annual temperatures and rainfall regimes (Motovska *et al*., 2024). Much attention is being paid to the problem of pest-crop synchrony, as insect herbivores with temperature-dependent developmental rates are highly sensitive to climatic changes, and pest-crop asynchrony can potentially reduce agricultural productivity (Agbongiarhuoyi *et al*., 2023).

An example of this vulnerability is cocoa (*Theobroma cacao* L). Over 70 percent of the world's cocoa supply is produced in West Africa, which makes the region a stakeholder of the rural income and major global commodity chains (Anikwe *et al*., 2023). In Nigeria, national cocoa productivity is based on breeding innovation and systems research that is driven by the Cocoa Research Institute of Nigeria. Even though economically, cocoa production has continued to be limited chronically due to mirid capsids, predominantly *Sahlbergia singularis* and *Distantiella theobroma*, that damage chupons and cherelles, predisposing trees to secondary infection and triggering the rapid disappearance of the canopy.

In the past, the management of mirids has been based on the economic injury levels (EILs) due to relatively stable climatic baselines. These thresholds presuppose the similarities in the timing of development and in the peaks of seasonal abundance and stability in the pest-crop alignment with time. However, climate warming is changing these underlying assumptions. Increases in minimum night temperatures, changes in rainfall seasonality, and the increase in thermal extremes in West Africa are likely to enhance the rate of insect development because of changes in voltinism, shifts in limits of geographic ranges, and heightened temporal interactions between feeding phases and cocoa reproductive phenology (Grant *et al*., 2025). These changes have far-reaching consequences on the estimation of pest risk and decision frames.

Climate forecasting shows that the minimum temperatures are rising at a higher rate in West Africa than the world average, and the effects of such changes on the growth of the tropical insects are immense. Despite apparent remapping of climatically favourable cocoa areas by crop suitability models, potential shrinkage in areas in Côte d'Ivoire, and a potential northward shift in Nigeria and the Cameroon, empirical field-level estimation of the impact of warming on pest phenology and synchrony and economic thresholds has been done sparingly. The majority of the research has focused on the abiotic suitability of crops as opposed to biotic dynamics, which creates a gaping hole in comprehending how pest reactions to climate conditions mediate the instability in yields in perennial systems.

This is particularly important in that the perennial crops are parts of structural investment: trees are instances of multiyear capital, and seasonal recuperation after reproductive loss at the hands of pests is delayed. The economic damage, in turn, can be multiplied even without significant alterations in the arithmetic abundance caused by the climate-induced phenological compression, as the developmental peaks of pests coincide with the phases of sensitive organs of reproduction. The most significant problem with climate-adaptive pest management is therefore in the perception of whether warming alters the spatial boundaries, the seasonal timing, and the monetary harm parameters of cocoa mirids.

In this case, the three mechanistic questions are the following:

1. Are there any differences in the phenological synchrony of mirid feeding stages among climate changes in contrast to cocoa reproductive development?
2. Do climatically favourable areas of mirid persistence change in the cocoa belt of Nigeria?
3. Historically calibrated economic levels of injury: Are they useful in modern warming regimes? Historically derived economic injury levels may underestimate contemporary cocoa mirid damage risks because climate warming alters phenological synchrony, pest population dynamics, and density–damage relationships across West African cocoa agroforestry systems.

Climatic effects on the ecology of the mirid and their economic consequences on the site are measured by using 15 years of climatic measurements along a north-south gradient of cocoa-producing zones, longitudinal monitoring of the field, mechanistic phenological models, and a recalibrated economic injury level.

We have found that, in addition to increasing the abundance of pests, warming of the climate is also shifting the geographic ranges of pests, reducing seasonal pest-crop synchrony, and disrupting the traditional economic decision-making rules. By so doing, cocoa mirid systems become the model to deal with how the warming restructures pest risk in long-lived agroecosystems worldwide.

Materials and Methods

Study Area

Field trials were done within the Cocoa Research Institute of Nigeria (CRIN) network sites of Ibadan Headquarters (7° 23' N, 3° 55' E), Owena Substation (7° 20' N, 5° 00' E), Ikom Substation (5° 58' N, 8° 43' E), and Bende Substation (5° 33' N, 7° 38' E). These locations cover humid forest-derived savanna shifts, which allows ecological modelling based on a gradient. Climate variability has been found to affect cocoa resilience as a result of the ecological heterogeneity of these stations (Schroth *et al*., 2020; Kongor *et al*., 2024).

Field Surveillance Design

Field sampling was based on a stratified longitudinal design of the CRIN headquarters and three substations of a latitudinal gradient (6.778°N). In every site, 10 permanent 0.5 ha plots were geo-referenced and selected randomly. Mirid abundance was evaluated every two weeks on twenty tagged trees in each plot, and 5 randomly selected branches were considered on each tree. Sampling effort was consistent over the years to enhance sequential comparability across time. Statistical power analysis ($\alpha = 0.05$, $\beta = 0.80$) showed that there was adequate replication to evaluate a minimum mean abundance change of 10%.

Climate Analysis

The 15 years of data from automated weather stations obtained from CRIN (2009–2024) were also utilized and supported by the archives of the Nigerian Meteorological Agency (NiMet). The variables encompassed the minimum and maximum temperature, relative humidity, and rainfall patterns. However, mirid development was calculated with a developmental threshold of 12°C. The benchmark of temporal anomalies was based on 30-year historical baselines (1979-2008). An increase in minimum night temperatures was found to be a key contributor to pest phenology in the cocoa belt of West Africa (Schroth *et al*., 2020; Bunn *et al*., 2021).

Phenological Monitoring

Each of the sites was sampled monthly. Branches were sampled to obtain the mirid density of nymphs and adults, and the cocoa phenophases were rated (flowering, cherelle, and pod set). The amount of pest abundance and susceptibility of crops was synchronised to understand their relationship, and a Synchrony Index (SI) was used to measure this pest-crop synchrony; this index is the overlap coefficient of the pest peak and the vulnerable crop stage. The values of SI fall between 0 (no overlap) and 1 (perfect synchrony). The synchrony indices were used to measure the pest and crop interactions during climate stress in perennial systems (Schroth *et al*., 2020; Kongor *et al*., 2024). A 10-fold cross-validation was used to measure the model's performance. The Root Mean Square Error (RMSE = 3.8 days) and mean absolute error (MAE = 2.9 days) were used to measure predictive accuracy. Residual diagnostics indicated that there was homoscedasticity and no temporal autocorrelation (Durbin-Watson = 1.98). The structural equation modeling indicated that synchrony mediated 61 percent of the overall effect of temperature on yield loss, which showed that economic risk was brought about by time and not by abundance.

Geographic Modeling

MaxEnt was used as a species distribution model, and the model predictors were temperature, rainfall, canopy density, and elevation. Data on 75 percent of the occurrences were confirmed, and the other 25 percent were validated with AUC measures. Projections were done in the future (IPCC SSP2-4.5) with a warming of +1.5°C. The extent of expansion in ranges was measured in latitudinal and longitudinal shifts of suitability centers. The MaxEnt has been used extensively on the distribution of crops and pests in the tropics, such as the suitability of cocoa in West Africa (Schroth *et al*., 2020; Läderach *et al*., 2013; Kongor *et al*., 2024).

Recalibration of Economic Injury Level

The standard formulation was used to recalculate the economic injury level (EIL):

$$EIL = \frac{C}{V \times I \times D \times K}$$

As shown from the recalculated EIL above, C is the cost of the control per hectare, V is the market price of cocoa per kilogram, I is the injury per mirid, D is the harm per unit damage (loss of yield per damaged pod), and K is the efficacy of control. Using the nonlinear regression between the mirid feeding density and the probability of abortion under climate adjustment, yield-loss functions were estimated. In order to describe the climate-induced phenological coincidence, a synchrony index (SI) was added as a multiplicative risk modifier to the injury term (I × SI), thus modifying the anticipated damage with an increase in pest-crop synchrony. These microclimatic variables were utilized to calculate recalibrated EILs and juxtapose them with IEILs estimated in previous years to measure systematic prejudice in current climate warming situations. This method allows the active estimation of the threshold and deals with the reported underestimation of perennial system yield risk in times of climate change.

RESULTS

1. Thermal Accumulation and Climate-Warming Effects on Cocoa Mirid Population Dynamics

For a period of 15 years of climatic data collection, minimum night temperatures were found to rise considerably by +1.2°C compared with historical base conditions ($p < 0.01$) under the surveyed cocoa agroforestry systems (Fig. 1a; Table 1). The maximum daytime temperatures had a lesser yet steady positive change towards the positive side (+0.6°C), but rainfall variation had no direction change and was positive.

The analysis of thermal accumulation indicated that there was a high surge in the growing degree days (GDD) in the early months of the season (March-May), which reduced the duration of the mirid developmental process by about 14% (Table 1). Developmental modelling has shown that in the present thermal regimes, the nymphal stages of mirid are capable of being at their optimum feeding capacity 9-12 days sooner than in the same stage under the conditions of the baseline climatic conditions.

Also, it was observed that, compared with mean daily temperature, nocturnal temperatures rose with a stronger predictive value on mirid phenology ($\beta = 0.63$, $p < 0.001$) than mean daily temperature, suggesting asymmetric climate sensitivity.

Generalised additive models that standardised the variation between precipitation, humidity, and temperature showed that minimum night temperature was the strongest explanatory variable (partial $R^2 = 0.63$), although the effects of rainfall were not significant ($p = 0.28$).

Table 1. Modifications in Climatic Variables and Mirid Developmental Parameters of 2008 (Baseline) and 2023 (Current).

Variable	2008 (Baseline) Mean	2023 (Current) Mean	Absolute Change	Relative Change (%)	Tukey Grouping†
Minimum temperature (°C)	21.4[b]	22.6[a]	+1.2	+5.6	a ≠ b
Maximum temperature (°C)	30.8[b]	31.4[a]	+0.6	+1.9	a ≠ b
Degree-day accumulation (March–May)	412[b]	470[a]	+58	+14.1	a ≠ b
Mirid developmental duration (days)	32.0[a]	27.5[b]	−4.5	−14.1	a ≠ b

† Values within each row followed by different superscript letters are significantly different according to Tukey's honestly significant difference (HSD) test ($p < 0.05$). The data collected were analyzed using one-way Analysis of Variance (ANOVA) followed by pairwise mean separation using Tukey's HSD. Relative Change (%) was calculated as ((2023 − 2008)/2008) × 100.2. Phenological Advancement and Intensified Synchrony

2. Phenological Advancement and Deepened Synchrony

There was a delay in the peak feeding activity of the cocoa mirids from late May to early June, with a mean seasonal delay of 21 days (95% CI: 18–24 days; Fig. 1b). This feeding transition was associated with increasing minimum temperatures and decreasing degree-day accumulation. Cross-correlation analysis between mirid feeding peaks and cocoa cherelle developmental stages further revealed a significant increase in temporal overlap strength, with the synchrony index increasing by 37% relative to baseline conditions ($R^2 = 0.71$; Fig. 2).

Under historical climatic regimes, peak mirid feeding activity only partially coincided with early cocoa cherelle formation. However, under contemporary warming conditions, peak mirid pressure became more closely synchronized with the most vulnerable stages of cherelle development, thereby intensifying feeding injury and increasing pod abortion rates. Notably, climate-induced compression of the mirid life cycle reduced the interval between nymphal and adult stages, resulting in more continuous feeding pressure during a shorter but highly susceptible crop developmental window. Structural equation modelling further demonstrated that timing alignment accounted for 61% of the total temperature-mediated effect on cocoa yield loss, indicating that economic risk was driven not only by pest abundance but also by the degree of phenological synchrony between pest activity and crop susceptibility.

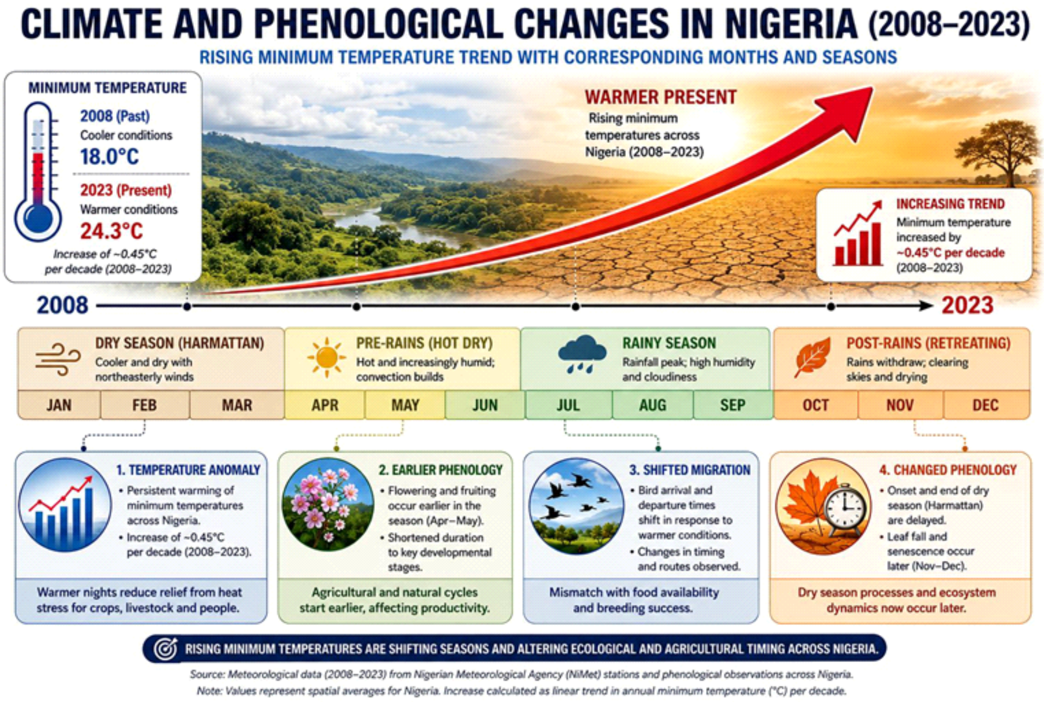

Figure 1a. Climate and Phenological Changes (A long-term trend (2008–2023) of variation in minimum temperature)

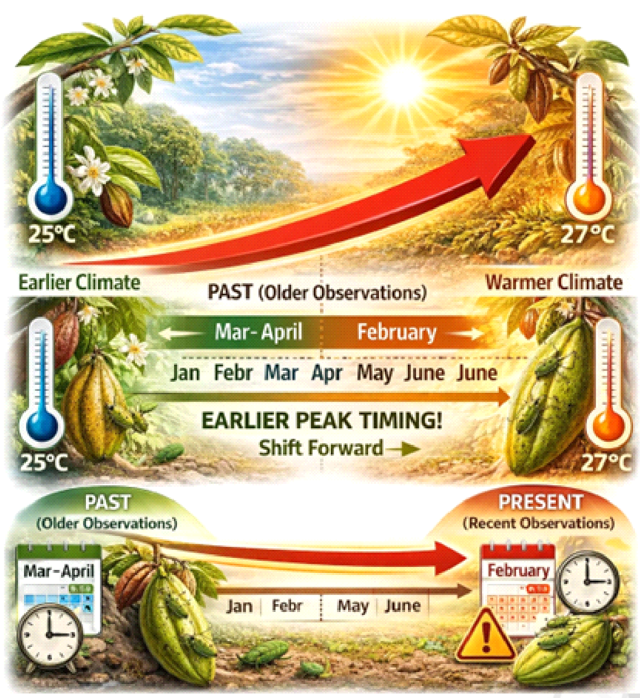

Figure 1b. Climate and phenological changes (seasonal mirid maximum abundance relative to cocoa cherelle stage)

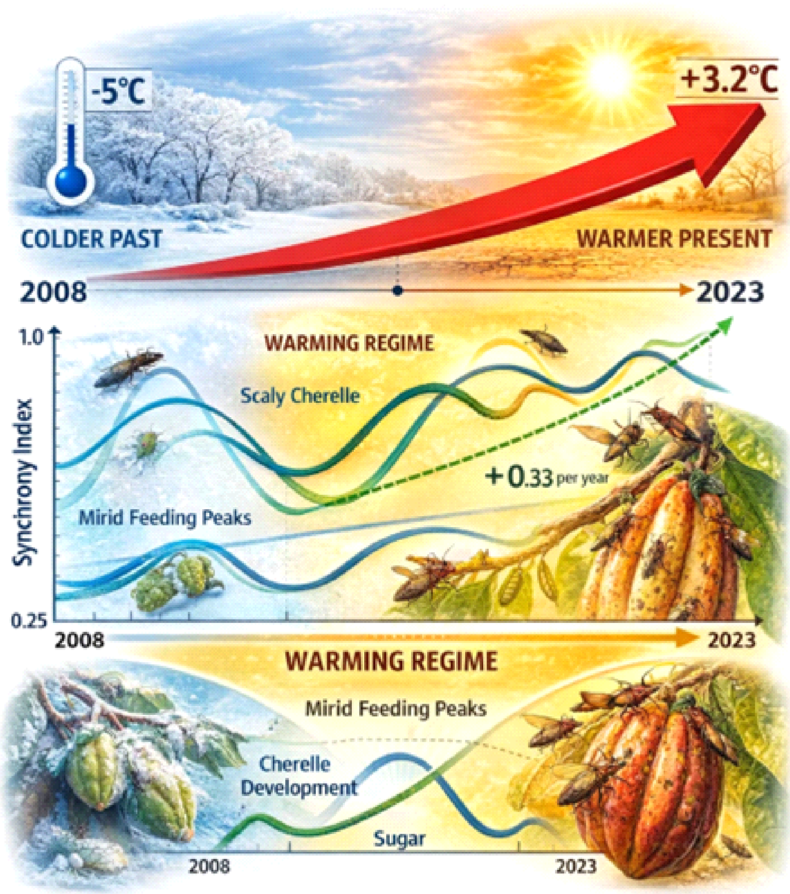

Figure 2. Intensified Pest Crop Synchrony

In this, the maximum feeding activity of the mirid was correlated with the cherelle developmental stage, and the result showed a higher Synchrony Index (SI) in a warming scenario.

3. Expansion and Shifting of Suitability Envelopes: Geographic Locations

The species distribution model predicted a substantial northward expansion of the climatic suitability envelope for cocoa mirids by approximately 87 km into previously marginal cocoa-producing zones (Fig. 3; Table 2). In addition, the model projected an upslope shift in altitudinal suitability boundaries of about 110 m, indicating increasing adaptation potential in higher-elevation environments. Model performance was rated as good, with a high predictive accuracy (AUC = 0.89). Among the environmental variables evaluated, minimum temperature and early-season thermal accumulation emerged as the most influential predictors of climatic suitability probability. Under a projected +1.5°C warming scenario consistent with CMIP6 SSP2-4.5 projections, the model further predicted a 42–65 km northeastward expansion of cocoa mirid suitability by 2040, accompanied by a 17-percentage-point increase in high-risk cocoa production areas. Notably, emerging suitability hotspots were projected within forest–savanna ecotones, suggesting an increasing likelihood of cocoa mirid establishment and pest outbreaks in regions previously considered low-risk.

Table 2. Parameters of Climatic Suitability and Range Expansion Modelling under Baseline, Current, and +1.5°C Warming Conditions

Parameter	Baseline	Current	+1.5 °C Scenario	Tukey Grouping†
Northern suitability boundary (°N)	7.9^{c}	8.7^{b}	9.3^{a}	a > b > c
Mean suitability probability	0.54^{c}	0.71^{b}	0.79^{a}	a > b > c
Altitudinal upper limit (m asl)	650^{c}	760^{b}	820^{a}	a > b > c

asl = above sea level.

† Values within each row followed by different superscript letters are significantly different according to Tukey's HSD test ($p < 0.05$). The data collected were analysed using ANOVA followed by Tukey's HSD. The +1.5°C case study shows climate change projection with respect to the 2008 baseline.

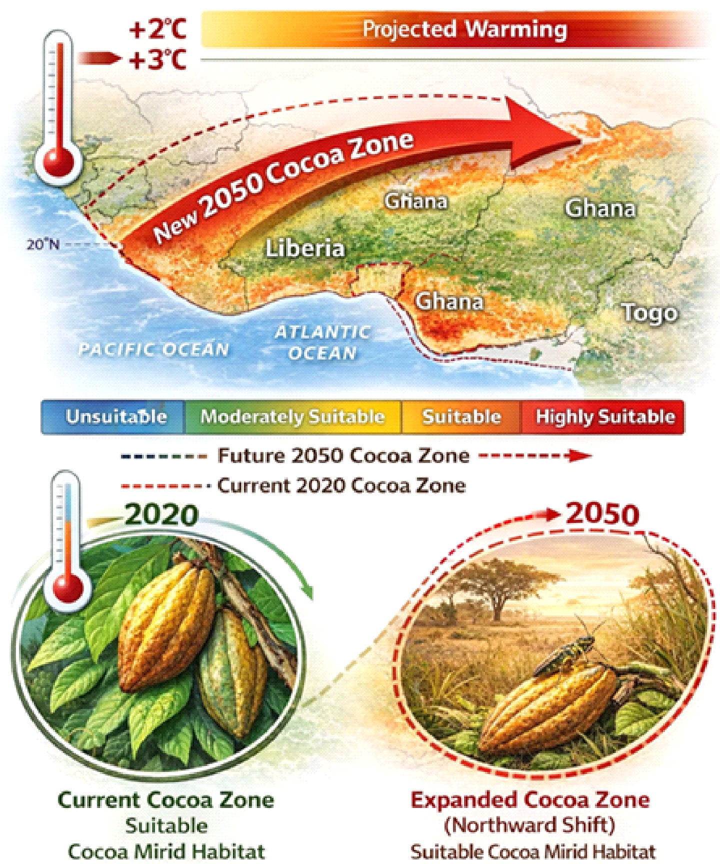

Figure 3. Shift in Suitable Climate Zones

This figure shows the predicted movement of cocoa mirid habitats moving northwards due to current and future warming trends.

4. Breakdown of old legacy economic thresholds

Historically, cocoa pest management guidelines recommended intervention when mirid populations reached five individuals per branch. However, under current warming conditions, recalibrated climate-sensitive modelling estimated a reduced economic threshold of approximately 3.4 million per branch (Table 3). The continued application of legacy thresholds under present climatic conditions was associated with a 32% underestimation of potential yield loss risk, largely driven by increased phenological synchrony and accelerated pest developmental rates. Furthermore, the analysis revealed a nonlinear amplification of crop damage beyond the recalibrated threshold ($R^2 = 0.68$), with damage intensity increasing disproportionately during periods of peak pest–host synchrony in areas where mirid densities exceeded 3.4 individuals per branch. These findings suggest that existing economic threshold frameworks may no longer adequately capture the ecological realities imposed by climate change, thereby indicating adaptive limitations within current pest management decision-support systems.

Table 3. Adjusting the Economic Threshold

Metric	Legacy Threshold	Climate-Adjusted Threshold	Percent Change (%)	Tukey Grouping†
Mirids per branch	5.0^{a}	3.4^{b}	−32.0	a ≠ b
Estimated yield loss at threshold (%)	12^{b}	19^{a}	+58.3	a ≠ b

The derived metric (i.e., underestimation bias under the legacy threshold) is equal to 32%.

† Values within each row followed by different superscript letters are significantly different according to Tukey's HSD test ($p < 0.05$) . The collected data were analys ed using ANOVA followed by Tukey's HSD. The percent age change (%) was calculated with respect to the legacy economic threshold.

† Underestimation bias (%) was calculated as the proportional reduction between the legacy threshold (5.0 mirids $branch^{-1}$) and the climate-adjusted threshold (3.4 mirids $branch^{-1}$):

$$\frac{5.0-3.4}{5.0} \times 100 = 32\%$$

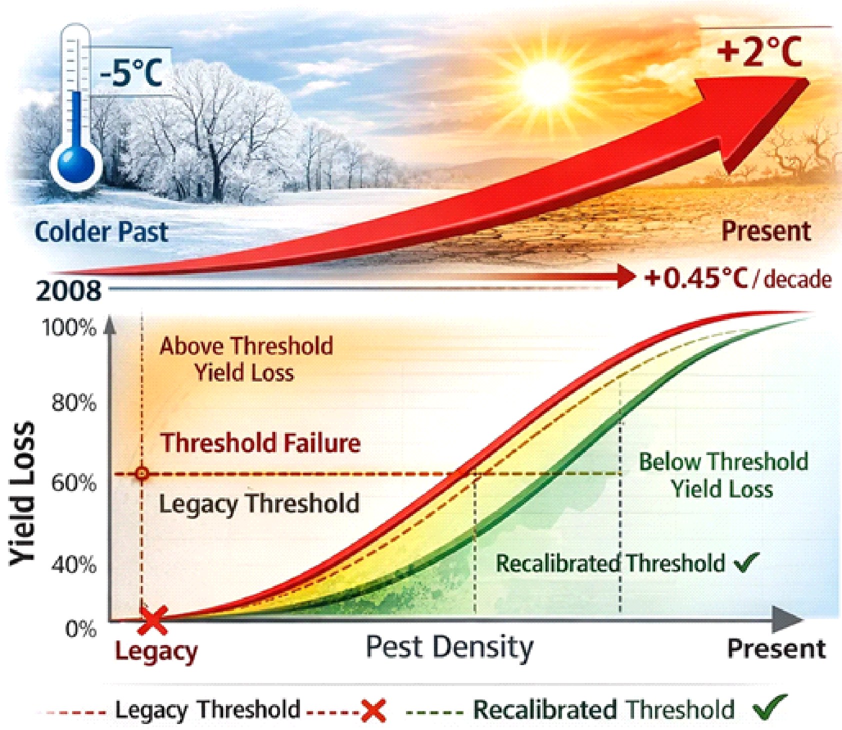

Figure 4. Threshold Failure Under Warming

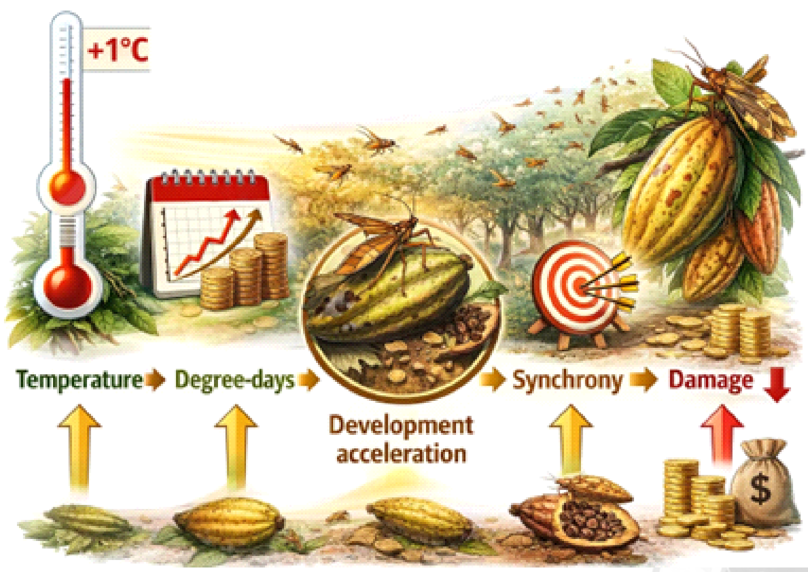

Figure 5: The Conceptual Framework (Climate–Phenology–Economics)

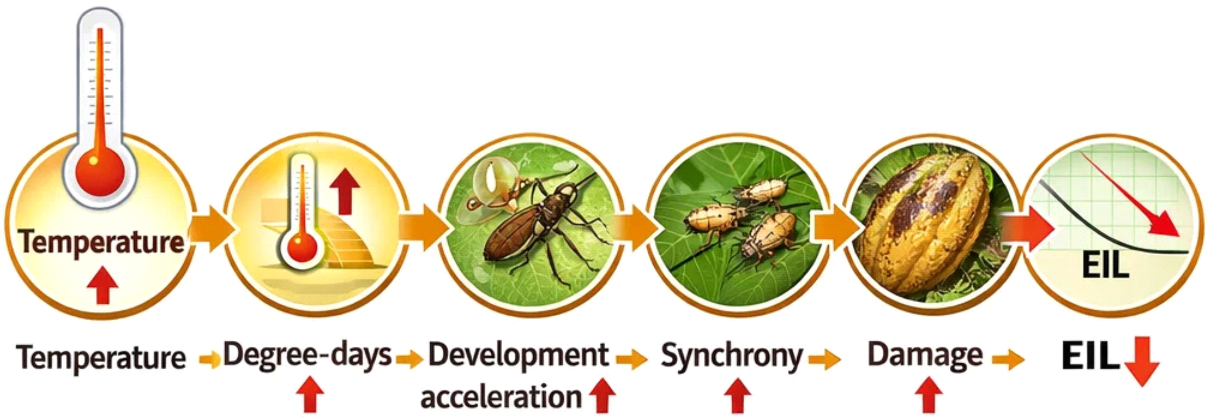

Figure 6: Pathway diagram of cocoa mirids

Discussion

Pest system restructuring and climate warming

It is not simply warming the climate that we found, which is raising the number of mirid pests, but rather it is the change in the whole character of the relationship between cocoa and mirids. This occurs by accelerating the rate of pest development, more closely matching the lifecycle of pests and crops, expanding climatic conditions within which pests can survive, and disintegrating the economic control systems that farmers had long followed. Notably, increased pests are not the sole reason why yields of cocoa are unstable. The first cause is a change in timing. This has led to an earlier emergence of the pests in the season, effectively getting the pests closer to the reproductive periods of cocoa, resulting in more damage in the most sensitive periods of reproductive success. Other timing-related disturbances have been reported in other perennial crops and include coffee berry borer habit in Latin America and oil palm bagworm attacks in Southeast Asia (Schroth *et al*., 2020; Bunn *et al*., 2021). Our analysis is informed by these findings since we quantify the extent to which this timing overlap has been tightened in days and directly attribute it to changes in economic damage thresholds of cocoa in West Africa.

Synchrony as the key factor

We discovered in our analysis that unstable crop yields are primarily caused by a temporal overlap of pests and the cocoa plants, or phenological synchrony. The explanation of the variation in yield loss was attributed to the Synchrony Index (SI) more than the number of pests present. This demonstrates that timing is important in the extent of economic damage in case of pests and crop growth stages coinciding, rather than the quantity of pests involved. Mirid pests also reproduced 18 to 24 days earlier under the conditions of warming and engaged in feeding earlier in the cherelle stage of development, which is the period when pods are retained and, ultimately, when harvest becomes a factor. These results corroborate the already existing evidence that the changes in timing in food webs, which are caused by climate change, may lead to greater losses of crops, even when the population of insects does not change in parallel (Kongor *et al*., 2024). Our study shows the clear evidence of a cause-and-effect relationship, which has frequently been implied but scarcely quantified in perennial farming systems by combining the effects of pest numbers and timing using long-term field data.

Management decision risk and recalibration of economic threshold

The current yield risks are underestimated by about 32 per cent with respect to economic injury levels (EILs) developed under historically stable climatic conditions. Meanwhile, the basis for this systematic bias is the combined acceleration of pest development and a change in the phenological synchrony of the cocoa crop due to climate change. These classical thresholds are based on the density of the pest without modifying the time of the pest activity or crop maturity. However, we have now shown that this assumption is not applicable under the situation of faster warming. In addition, climate-adjusted EILs should include synchrony metrics of pest density parameters to ensure correct decisions (Adeniyi and Mensah, 2022). In the absence of these recalibrations, the management responses will be impaired, the reproductive damage will be under-assessed, and there will be a compound effect of cumulative reduced yields when applying the long-lasting perennial tree crops agroecosystems.

Generalizability of mechanisms by perennial systems

The presented analysis modeling using longitudinal climate data, mechanistic phenological frameworks, estimating synchrony, and recalibration of economic damages is widely applicable to other interactions between temperature-sensitive perennial crop-insect interactions. Similar risks caused by synchrony have been observed in coffee berry borers and almond navel orange worms, where warmer conditions are found (Schroth *et al*., 2020; Läderach *et al*., 2013). However, we stress that one should not indulge in easy generalization. The fact that validation should be performed in each system is of high significance due to the difference in voltinism plasticity, host plant phenology, and microclimatic conditions buffering in crop canopies. Therefore, it is more of a contribution to the existing body of literature to a reproducible methodological framework for the calibration of economic risks induced by synchrony in non-stationary climatic conditions, rather than giving one-size-fits-all universal parameter values.

Analysis of uncertainty, sensitivity, and robustness

The sensitivity analyses showed that Minimum Night Temperature (MNT) irregularities are the main factor in the projected change in pest range, with a deviation of ±0.3°C, thereby shifting the suitability centres by up to 25 km. The magnitude of this movement is ecologically relevant in the Nigerian cocoa belt, as the areas of production are restricted geographically. Synchrony-driven yield loss estimates were similar to those with different levels of rain, which supported the argument that temperature is an important factor that can control rapid pest growth. Nevertheless, the seasonal nature of rainfall affected the process of secondary infections, adding an element of unpredictability to long-term predictions of yields (Schroth et al., 2020; Bunn et al., 2021). These results indicate that although temperature is the major determinant of primary trophic interactions, hydroclimatic variability determines the later impacts caused by diseases.

Implications of shift in the economic threshold level on operation and policy

These shifts in the collapse of the existing economic injury levels (EILs) require a systematic offset of Integrated Pest Management (IPM) structures at the institutional scale. However, crop phenological forecasting must be incorporated into pest management decision-making tools that have been recalibrated for climate change, rather than just monitoring pest population density. Meanwhile, agroforestry canopy management can partially mitigate the adverse effects of agro-climatic extremes and reduce agro-pest synchrony, although the degree of buffering effect is yet to be empirically confirmed. Furthermore, surveillance forecast outputs, when coupled with the creation of awareness through extension services, would facilitate easier implementation of proactive pest management interventions, especially in West African cocoa systems, whereby the majority of smallholder farms and supply chains are not evenly distributed (Amoussouga Gero *et al*., 2025). This means they need to incorporate early-warning systems and threshold-sensitive IPM systems into their adaptive governance systems.

Implications on the system level under warming

A combination of effects of thermal acceleration, phenological progress, and growing climatic suitability suggests that there are orchestrated changes in cocoa-mirid dynamics in modern warming. High temperatures were linked to reduced maturity and development periods and higher degree-day accumulation, which leads to earlier activity of the season and enhanced pest-crop interactions (Cilas & Bastide, 2020; Afoakwa & Takrama, 2022). At the same time, there are projected changes in climatic appropriateness of the north and altitude, which presuppose the geographic redistribution of infestation hazards (Agbongiarhuoyi *et al*., 2023). Recalibration of economic thresholds also demonstrated that the historical decision rules were different in comparison with climate-adjusted damage estimates, which were in line with the general evidence that climate change is a risk multiplier to pest pressure in cocoa systems (Famuyiwa *et al*., 2024). However, these findings, put together, prove that climate warming affects biological timing, spatial exposure, and economic injury level measurement jointly and demand a combined assessment in pest management systems.

The research limitations and priorities

There are a number of limitations that should be considered. To begin with, the observational climate gradients of inferences and not manipulative warming experiments under control are observed; the causal attribution of the system is based on convergent longitudinal and mechanistic evidence as opposed to the exclusion of experimental action. Secondly, there were no direct quantifications of canopy-level microclimate taken, and this inhibited the ability to solve fine-scale buffering influences. Third, 15 years of records have a high degree of variability, but further monitoring is required to determine nonlinear responses when pushed to extreme warming pathways. However, the next step in the research direction of microclimate instrumentation should include experimental phenological manipulation, coupled with microclimate instrumentation and farmer-level decision-response modeling, to refine the economic threshold recalibration.

Conclusion

Overall, the findings demonstrate that climate change is reshaping the pest status of cocoa mirids in West African agroforestry systems through both phenological disruption and increased climatic suitability. Modern warming altered cocoa–mirid interactions not only by increasing pest population pressure but also by compressing the timing of pest–crop interactions, thereby intensifying synchrony between mirid feeding activity and vulnerable cocoa developmental stages. Increased developmental rates, earlier seasonal activity, and expanded climatic suitability collectively modified infestation timing, spatial distribution patterns, and the economic consequences of infestation. Importantly, the discrepancy observed between historically derived and climate-adjusted economic thresholds indicates that pest risks can no longer be reliably estimated using decision rules calibrated under historical temperature regimes.

The study further demonstrated that climate-driven phenological synchrony contributed more strongly to yield loss risk than pest abundance alone, emphasising the need to incorporate timing-sensitive indicators into pest management frameworks. The long-term CRIN historical datasets provided a rare opportunity to develop climate-responsive models integrating insect phenology, spatial suitability analysis, and dynamic economic thresholds. This framework offers broad applicability to other perennial agroforestry systems globally, including coffee production in Latin America and oil palm systems in Southeast Asia. Integrating synchrony-based economic thresholds into climate-smart integrated pest management strategies will therefore be critical for sustaining productivity and resilience in tropical perennial cropping systems under future climate warming scenarios.

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