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Threshold responses of Okra (*Abelmoschus esculentus* l. moench) to increasing densities of adult *Nisotra dilecta* Dalman (coleoptera: chrysomelidae): implications for crop damage and yield loss

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Abstract
Adult flea beetles (*Nisotra dilecta* Dalman) are important defoliators of okra, yet quantitative information on crop responses to increasing infestation densities is limited. This study evaluated the threshold responses of okra to increasing densities of adult *N. dilecta* under screen-house and field conditions at Joseph Sarwuan Tarka University, Makurdi, Nigeria. Six infestation densities (0, 5, 10, 20, 30 and 40 adult pairs per cage) were assessed in completely randomized and randomized complete block designs for the screen-house and field experiments, respectively. Increasing beetle density significantly ($P < 0.001$) increased foliar injury while progressively reducing vegetative growth, delaying flowering and depressing yield. Relative to the uninfested control, shoot height declined by 5.2–67.2% in the early season and 4.7–54.4% in the late season, whereas shoot biomass decreased by up to 71.0 and 71.8%, respectively. Fresh fruit yield declined by 11.0–67.6% in the early season and 12.2–70.6% in the late season. Beetle density showed strong positive correlations with leaf damage ($r = 0.901–0.938$; $P < 0.001$) and strong negative correlations with growth and yield attributes ($|r| = 0.718–0.927$; $P < 0.001$). Second-order polynomial models ($R^2 = 0.85–0.91$) identified a distinct threshold response, with rapid deterioration in crop performance beyond approximately 10–20 adult pairs per cage. These findings indicate that okra can tolerate low *N. dilecta* infestations; however, beetle densities exceeding approximately 20-pairs (8 adults per plant) result in marked physiological stress and economically important yield losses, providing a quantitative basis for establishing economic thresholds and developing evidence-based integrated pest management strategies.

Keywords: *Abelmoschus esculentus*, density-dependent herbivory, flea beetle, physiological stress, threshold response, integrated pest management

Introduction

Okra (*Abelmoschus esculentus* (L.) Moench) is an important vegetable crop cultivated throughout tropical and subtropical regions for its nutritional, medicinal and economic value (Ibitoye and Kolawole, 2022; Yildiz *et al*., 2025) [8, 17] The immature pods are rich in dietary fibre, vitamins, minerals and bioactive compounds, while the crop constitutes an important source of food, nutrition and income for millions of smallholder farmers across tropical and subtropical regions (Gemede *et al*., 2016; Alabi *et al*., 2023; Massrie, 2025) [7, 2, 10]. In Nigeria, okra is grown across diverse agroecological zones and is consumed fresh, dried or processed into various food products, making it one of the country's most important indigenous vegetables.

Despite its economic importance, okra productivity remains constrained by numerous biotic stresses, among which insect pests constitute one of the most serious limitations (Araba *et al*., 2025; Ekoja *et al*., 2023) [3, 4]. Defoliating insects are particularly damaging because they reduce the photosynthetically active leaf area required for biomass accumulation and fruit development. Severe foliar injury during the vegetative stage disrupts plant growth, delays reproductive development and ultimately reduces marketable yield (Erb & Reymond, 2019; Ekoja *et al*., 2023) [5, 4]. Consequently, effective management of foliar-feeding pests is essential for sustainable okra production.

Among the major defoliators of okra in West Africa are flea beetles (Coleoptera: Chrysomelidae), including species of *Podagrica* and *Nisotra*, whose adults produce characteristic "buckshot" feeding holes on leaves (Ekoja *et al*., 2023; Ojiako *et al*., 2023) [4, 11]. Persistent feeding by high beetle populations can result in extensive defoliation, reduced photosynthesis and substantial yield losses, particularly when infestations occur early in crop development (Adesina *et al*. 2018) [1]. While *Podagrica* species have received considerable attention because of their widespread occurrence on okra, comparatively little information is available on the damage potential and crop response to infestation by *Nisotra dilecta* Dalman under controlled infestation levels.

Plant responses to herbivory are strongly influenced by insect density. At low infestation levels, plants may compensate for tissue loss through physiological adjustments such as increased photosynthetic efficiency, assimilate redistribution and production of new foliage. However, as herbivore pressure increases, these compensatory mechanisms become progressively less effective, leading to reduced growth, delayed flowering and yield decline (Züst & Agrawal, 2017; Erb & Reymond, 2019) [18, 5]. Consequently, crop damage is often non-linear, with relatively small effects at low pest densities followed by rapid deterioration once a critical infestation threshold is exceeded (Paredes *et al*., 2022) [12]. Understanding these threshold responses is fundamental to integrated pest management because it provides the biological basis for developing economic injury levels and action thresholds that optimize pest control while minimizing unnecessary insecticide applications (Pedigo & Rice, 2014) [13].

Despite the recognized importance of flea beetles as major defoliators of okra, quantitative information describing crop responses across increasing densities of *Nisotra dilecta* remains scarce. This study therefore quantified density-dependent effects of adult *N. dilecta* on foliar injury, vegetative growth, reproductive development, biomass accumulation and fruit yield to identify biologically meaningful damage thresholds relevant to integrated pest management.

Materials and methods

Study site

The study was conduct in 2022 at the Teaching and Research Farms of Joseph Sarwuan Tarka University, Makurdi, Benue State, Nigeria (7°44′N, 8°32′E). The investigation comprised two complementary experiments designed to evaluate the response of okra to increasing densities of adult *Nisotra dilecta* Dalman. A screen-house experiment was conducted during the early planting season (March–June 2022), followed by a field experiment during the late planting season (June–September 2022) under natural field conditions.

Plant material

The okra cultivar LD-88, an improved open-pollinated variety developed by the National Horticultural Research Institute (NIHORT), Ibadan, Nigeria, was used throughout the study. The variety is characterized by vigorous growth, dark-green spiny pods, high mucilage content and wide adaptation to the Nigerian agroecological conditions.

Insect culture

Adult *N. dilecta* used for the experiments were obtained from naturally infested okra fields at the Teaching and Research Farms of the Joseph Sarwuan Tarka University, Makurdi. The colony was maintained on potted okra plants enclosed in insect-proof wire-mesh cages (25 × 25 × 30 cm). Approximately twenty pairs of newly collected adults were introduced into each cage for oviposition and removed after 21 days. The soil in each pot was subsequently monitored daily for adult emergence. Newly emerged adults of uniform age were collected and used for all infestations. Throughout the culture period, insects were maintained under ambient laboratory conditions (24–28°C and 79–92% relative humidity).

Screen-house experiment

The screen-house experiment was conducted from March to June 2022. Okra was established in 10-L plastic pots filled with well-mixed loamy soil. Three seeds were sown per pot and thinned to one vigorous seedling one week after emergence. At three weeks after sowing (WAS), corresponding to the vegetative stage, five potted plants were enclosed in each insect-proof wire-mesh cage (1.2 × 1.2 × 2.0 m).

Six infestation treatments comprising 0 (control), 5, 10, 20, 30 and 40 pairs of adult *Nisotra dilecta* per cage were imposed using newly emerged adults transferred with an aspirator. Treatments were arranged in a completely randomized design with three replicates, giving a total of 18 cages (90 plants). Assigned beetle densities were maintained throughout the experimental period by replacing dead adults daily with individuals of the same sex and approximately the same age from the laboratory colony. Plants were watered as required to maintain optimum growth.

Field experiment

The field experiment was conducted during the late planting season (June to September 2022) at the Teaching and Research Farms of Joseph Sarwuan Tarka University, Makurdi. The land was manually prepared, and okra was planted at a spacing of 60 × 30 cm. Three seeds were sown per planting hole and thinned to one healthy plant after emergence. At three WAS, insect-proof wire-mesh cages (1.2 × 1.2 × 2.0 m) were installed over groups of five uniform plants, after which adult *N. dilecta* were introduced at the same infestation densities used in the screen-house experiment (0, 5, 10, 20, 30 and 40 pairs per cage).

The treatments were arranged in a randomized complete block design with three replicates, giving 18 cages enclosing 90 plants. Manual weeding and other agronomic practices were carried out uniformly across treatments. Beetle populations were maintained at their assigned densities throughout the experiment by replacing dead individuals daily with adults of similar age and sex from the laboratory culture.

Data collection

Observations were recorded at 3, 6, 9, 12 and 15 WAS. Plant height was measured from the stem base to the apical growing point. Leaf damage was quantified as the area removed by adult feeding using the graph-paper method (Walter and Hund, 2015). At 9 WAS, the total number of leaves and the number of damaged leaves per plant were counted to estimate the percentage of damaged leaves. A leaf was classified as damaged when it exhibited one or more characteristic feeding perforations ("buckshot" lesions) produced by *N. dilecta*.

Flowering was assessed as the number of days required to attain 50% flowering within each treatment. At harvest, the number of fruits per plant, fresh fruit weight, fruit length, fruit diameter, number of seeds per fruit, 100-seed weight, shoot fresh weight and shoot dry weight were determined using standard procedures. Percentage fruit yield reduction relative to the uninfested control was also calculated.

Statistical analyses

Data from the screen-house and field experiments were analysed separately using the General Linear Model (PROC GLM) procedure in SAS software version 9.2 (SAS Institute, 2009) [15]. Analysis of variance (ANOVA) was used to evaluate the effects of *Nisotra dilecta* infestation density on growth and yield variables. Treatment means were separated using Tukey's Honestly Significant Difference (HSD) test at $P \leq 0.05$. Pearson's correlation coefficients were computed to quantify associations between beetle density and plant response variables. First- and second-order polynomial regression models were fitted to describe the relationship between *N. dilecta* density and plant response variables. The best-fitting model was selected based on the coefficient of determination (R^2), significance of regression coefficients, and biological interpretability.

Results

Threshold responses of okra leaf damage to increasing densities of adult *Nisotra dilecta*

Leaves were the primary feeding sites of adult *N. dilecta*, with feeding commencing almost immediately after beetle introduction. Adults fed indiscriminately on both adaxial and abaxial leaf surfaces, producing the characteristic circular "buckshot" lesions (approximately 1.0–2.0 mm² per feeding hole) that progressively coalesced as infestation intensified. The magnitude of leaf injury increased significantly with beetle density throughout the cropping period (Figure 1).

In both planting seasons, cumulative leaf area damaged differed significantly among infestation levels, with plants exposed to 20 and 40 adult pairs sustaining substantially greater injury than those infested with lower beetle densities ($P < 0.001$). No feeding damage was observed on control plants throughout the experiment. While feeding by 5 and 10 beetle pairs was largely confined to recently expanded leaves located in the middle canopy, infestations of ≥20 pairs resulted in indiscriminate feeding across young, mature and senescing leaves, indicating a breakdown of feeding selectivity under high population pressure.

Temporal patterns of damage further demonstrated a density-dependent response. Leaf area consumed continued to increase progressively at the 5- and 10-pair infestation levels throughout the observation period, whereas damage at the 20- and 40-pair densities approached saturation after 12 weeks after sowing (WAS) during the early season and after 10 WAS during the late season. By crop maturity, virtually every leaf on plants subjected to beetle infestation exhibited feeding injury irrespective of infestation density, although lesion abundance remained greatest under the highest beetle populations.

Vegetative growth responses to beetle-induced stress

Increasing infestation density markedly suppressed vegetative development of okra (Table 1). Significant reductions were observed in leaf production (Early: F = 32.63, df = 4, 8, P < 0.001; Late: F = 37.00, df = 4, 8, P < 0.001), branch formation (Early: F = 10.53, df = 4, 8, P < 0.001; Late: F = 12.18, df = 4, 8, P < 0.001), stem diameter (Early: F = 32.37, df = 4, 8, P < 0.001; Late: F = 55.22, df = 4, 8, P < 0.001), and shoot height (Early: F = 76.37, df = 4, 8, P < 0.001; Late: F = 52.84, df = 4, 8, P < 0.001).

The effects of infestation were strongly density dependent. Plants exposed to only five beetle pairs maintained vegetative growth comparable with the uninfested control (P > 0.05), whereas infestations of 20 and 40 pairs caused severe suppression of all measured growth parameters. Leaf production declined by 7.8–64.7% during the early season and by 7.7–59.0% during the late season relative to the control. Likewise, shoot height decreased by 5.2–67.2% and 4.7–54.4% in the respective planting seasons.

Visual observations supported these quantitative results. Plants exposed to the two highest infestation levels exhibited persistent stunting, sparse foliage, reduced branching and poor canopy development throughout the growing period (Plate 1), whereas plants in the control and 5-pair treatments maintained vigorous vegetative growth. Regardless of infestation level, shoot elongation had largely ceased by approximately 12 WAS, indicating that the major effects of beetle feeding occurred during active vegetative growth.

Reproductive development and yield responses

Increasing densities of *N. dilecta* significantly delayed reproductive development of okra (Figure 2). The time required to attain 50% flowering increased progressively with infestation density and differed significantly among treatments (Early: F = 76.37, df = 4, 8, P < 0.001; Late: F = 52.84, df = 4, 8, P < 0.001). Plants infested with 20 and 40 beetle pairs flowered substantially later than those subjected to lower infestation densities, whereas flowering time in the 5-pair treatment remained statistically comparable to the control (P > 0.05).

The reduction in reproductive performance closely paralleled the decline in vegetative growth (Table 2). Beetle infestation significantly reduced fruit number (Early: F = 73.86, df = 4, 8, P < 0.001; Late: F = 87.43, df = 4, 8, P < 0.001), fresh fruit weight (Early: F = 116.95, df = 4, 8, P < 0.001; Late: F = 245.31, df = 4, 8, P < 0.001), seeds per fruit (Early: F = 129.43, df = 4, 8, P < 0.001; Late: F = 159.69, df = 4, 8, P < 0.001), and 100-seed weight (Early: F = 28.10, df = 4, 8, P < 0.001; Late: F = 30.54, df = 4, 8, P < 0.001). Yield losses became particularly pronounced once beetle density reached 20 pairs per cage, with no appreciable improvement observed between the 20- and 40-pair treatments.

Consistent with these responses, shoot biomass declined by 12.6–71.0% in the early season and by 6.2–71.8% in the late season, while fresh fruit yield decreased by 11.0–67.6% and 12.2–70.6%, respectively (Table 3). Shoot biomass differed significantly among infestation levels (Early: F = 61.26, df = 4, 8, P < 0.001; Late: F = 65.99, df = 4, 8, P < 0.001), as did marketable fruit yield (Early: F = 23.98, df = 4, 8, P < 0.001; Late: F = 40.42, df = 4, 8, P < 0.001). Notably, biomass and fruit yield obtained from plants exposed to 5 and 10 beetle pairs did not differ significantly from the uninfested control (P > 0.05), whereas infestations of 20 and 40 pairs caused substantial reductions in both parameters.

Relationships between beetle density and crop performance

Correlation analysis confirmed that increasing beetle density was closely associated with progressive deterioration in crop performance (Table 4). Beetle density was strongly and positively correlated with cumulative leaf area damaged in both the early (r = 0.938, n = 15, P < 0.001) and late (r = 0.901, n = 15, P < 0.001) planting seasons. Conversely, infestation density exhibited strong negative correlations with virtually all vegetative and reproductive traits measured, with correlation coefficients exceeding |0.79| during the early season and |0.71| during the late season (P < 0.001), indicating that increasing feeding pressure consistently impaired crop growth and productivity.

The density-dependent nature of these responses was further demonstrated by second-order polynomial regressions. Beetle density explained a high proportion of the variation in shoot height (Early: $Y = 0.043x^2 - 3.2342x + 99.328$, R^2 = 0.907; Late: $Y = 0.0401x^2 - 2.7654x + 81.279$, R^2 = 0.907) and fresh fruit yield (Early: $Y = 0.0052x^2 - 0.3811x + 9.807$, R^2 = 0.8593; Late: $Y = 0.0033x^2 - 0.2664x + 7.2678$, R^2 = 0.8499). The fitted curves revealed a distinct threshold response, with relatively modest reductions in crop performance at low infestation densities followed by a steep decline once beetle populations exceeded approximately 10–20 adult pairs per cage. This pattern was consistently reflected in the integrated stress-response profile (Figure 3), where increasing feeding pressure simultaneously intensified foliar injury while progressively reducing vegetative growth, biomass accumulation and fruit yield.

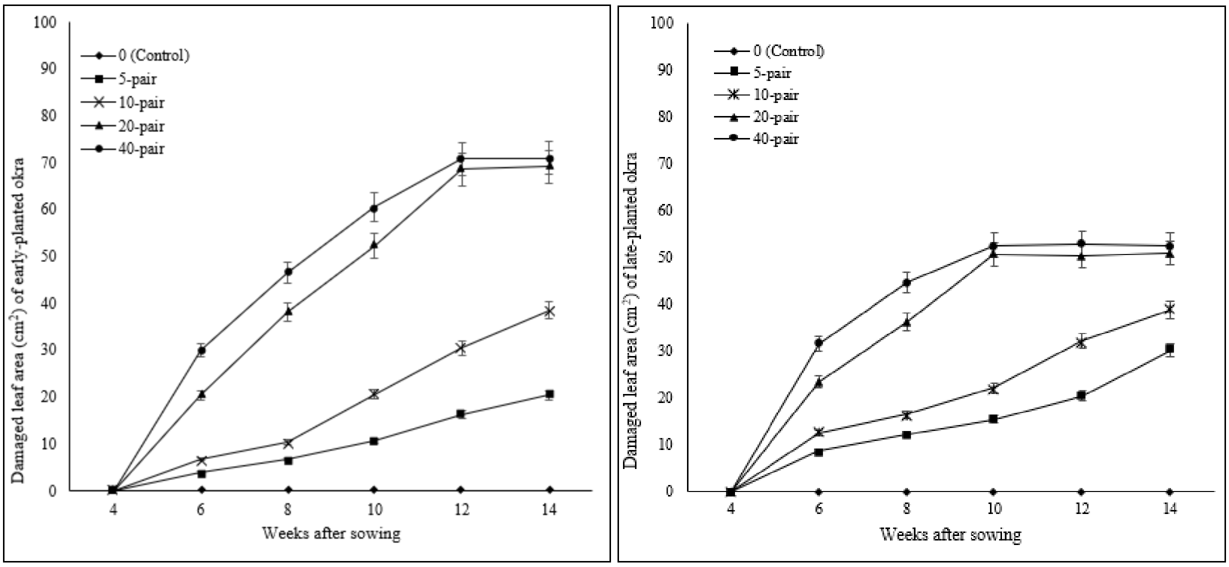

Fig 1: Temporal progression of leaf damage in okra exposed to increasing densities of adult *Nisotra dilecta* during early- and late-season cropping.

Values represent mean leaf area damaged per plant measured at successive weeks after sowing under five adult beetle infestation densities. Error bars represent standard errors of the means.

Table 1: Vegetative growth responses of okra to increasing infestation densities of adult *Nisotra dilecta*.

	Number of leaves per plant		**Number of branches per plant**		**Stem diameter (cm)**		**Shoot height (cm)**	
Beetle Density	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**
0	17.00 ± 0.58 a	13.00 ± 0.58 a	2.67 ± 0.33 a	1.67 ± 0.33 a	2.06 ± 0.08 a	1.85 ± 0.09 a	93.67 ± 3.18 a	77.56 ± 1.44 a
5	15.67 ± 0.67 a	12.00 ± 0.58 ab	2.00 ± 0.00 a	1.67 ± 0.33 a	1.95 ± 0.03 a	1.72 ± 0.12 a	88.83 ± 1.09 ab	73.92 ± 2.31 a
10	13.33 ± 0.88 a	9.67 ± 0.67 b	1.67 ± 0.33 b	0.00 ± 0.00 b	1.84 ± 0.09 a	1.60 ± 0.03 a	78.33 ± 4.63 b	58.00 ± 4.93 b
20	7.67 ± 0.67 b	6.00 ± 0.58 c	0.00 ± 0.00 c	0.00 ± 0.00 b	1.25 ± 0.15 b	1.03 ± 0.09 b	44.56 ± 2.92 c	39.33 ± 3.48 c
40	6.00 ± 1.15 b	5.33 ± 0.88 c	0.00 ± 0.00 c	0.00 ± 0.00 b	0.97 ± 0.03 b	0.89 ± 0.07 b	40.11 ± 1.16 c	35.33 ± 2.03 c
F-value	32.63	37.00	10.53	12.18	32.37	55.22	76.37	52.84
P-value	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	<0.001	<0.001
Cv (%)	12.38	10.67	20.43	58.38	9.01	7.19	7.20	8.10

Values are means ± standard error (SE) of three replications. Means within a column followed by the same lowercase letter are not significantly different according to Tukey's HSD test (P> 0.05). *F*-values are derived from one-way ANOVA. Cv = coefficient of variation. Beetle density refers to the number of adult pairs released per screen cage

A. High-density beetle infestation causing severe feeding damage, stunted growth, reduced branching and diminished leaf development.
B. Uninfested control plant exhibiting normal vegetative growth, extensive foliage and vigorous branching

Plate 1: Representative growth responses of okra subjected to contrasting levels of *Nisotra dilecta*-induced feeding stress

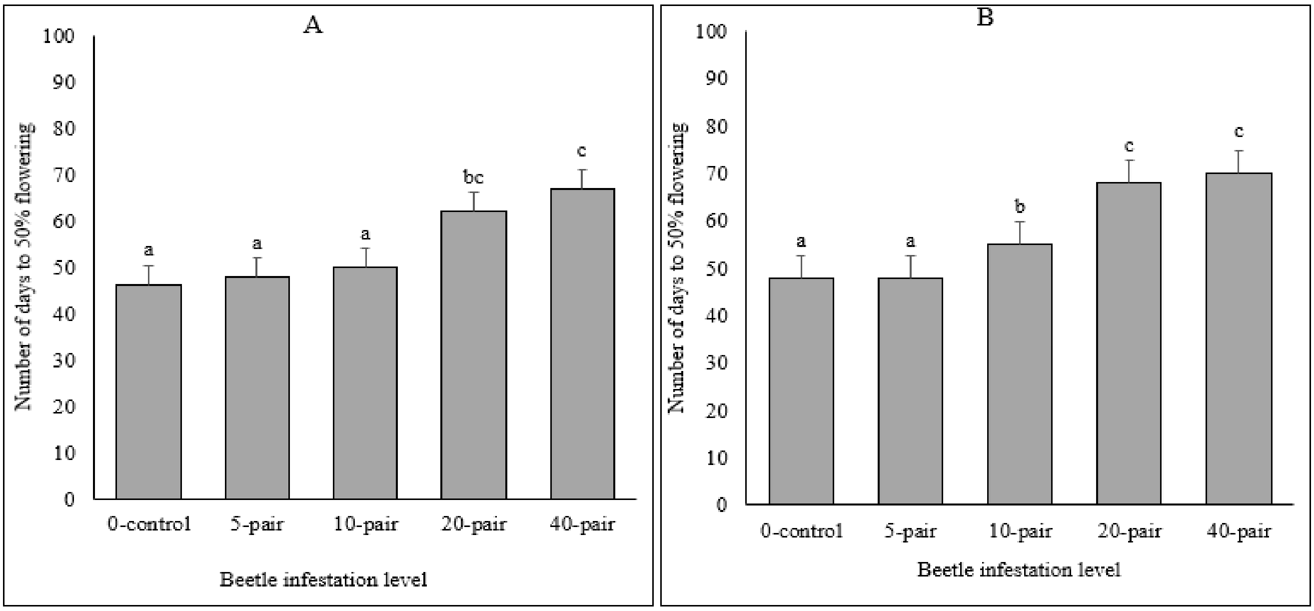

Fig 2: Delay in flowering of okra induced by increasing infestation densities of adult *Nisotra dilecta*.

Columns bearing different letters differ significantly according to Tukey's HSD test (P> 0.05); Panel A = Early season; Panel B = Late season.

Table 2: Reproductive responses and seed production of okra under increasing densities of adult *Nisotra dilecta*

	Number of fruits per plant		Fresh fruit weight per plant (g)		Number of seeds per fruit		100-seed weight (g)	
Beetle Density	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**
0	11.00 ± 0.58 a	9.33 ± 0.33 a	206.31 ± 8.09 a	192.17 ± 1.74 a	110.03 ± 5.77 a	92.00 ± 1.73 a	6.13 ± 0.18 a	5.28 ± 0.17 a
5	9.67 ± 0.33 ab	8.67 ± 0.33 a	203.31 ± 9.24 a	188.06 ± 4.37 a	97.00 ± 1.53 ab	90.67 ± 3.48 a	6.01 ± 0.26 ab	5.07 ± 0.06 a
10	8.87 ± 0.13 b	8.33 ± 0.33 a	194.04 ± 2.31 a	161.79 ± 6.93 b	91.00 ± 2.08 b	76.00 ± 3.06 b	5.06 ± 0.06 b	4.67 ± 0.33 a
20	4.44 ± 0.29 c	3.33 ± 0.33 b	63.33 ± 8.82 b	58.06 ± 6.61 c	42.43 ± 4.64 c	35.87 ± 2.07 c	3.92 ± 0.51 c	3.46 ± 0.23 b
40	3.56 ± 0.29 c	2.67 ± 0.33 b	50.92 ± 2.14 b	39.62 ± 2.60 c	32.20 ± 1.74 c	31.83 ± 0.73 c	3.83 ± 0.46 c	3.17 ± 0.17 b
F-value	73.86	87.43	116.95	245.31	129.43	159.69	28.10	30.54
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cv (%)	8.87	9.15	8.83	6.35	7.12	6.17	7.12	6.95

Values are means ± standard error (SE) of three replications. Means within a column followed by the same lowercase letter are not significantly different according to Tukey's HSD test (P> 0.05). F-values are derived from one-way ANOVA. Cv = coefficient of variation. Beetle density refers to the number of adult pairs released per screen cage

Table 3: Biomass accumulation and marketable fruit yield losses associated with increasing densities of adult *Nisotra dilecta*.

	Shoot biomass (g $plant^{-1}$)				Fresh fruit yield (tha^{-1})			
Beetle density	**Early**	**% reduction**	**Late**	**% reduction**	**Early**	**% reduction**	**Late**	**% reduction**
0	50.91 ± 2.31 a	0.0	43.52 ± 2.02 a	0.0	9.29 ± 0.65 a	0.0	6.91 ± 0.50 a	0.0
5	44.47 ± 1.81 a	12.6	40.83 ± 1.74 a	6.2	8.27 ± 0.82 a	6.2	6.07 ± 0.64 a	12.2
10	39.13 ± 2.49 a	23.1	36.33 ± 3.28 a	16.5	7.47 ± 0.29 a	16.5	5.81 ± 0.42 a	15.9
20	17.83 ± 1.74 c	65.0	15.33 ± 1.20 b	64.8	3.44 ± 0.29 b	64.8	2.59 ± 0.30 b	62.5
40	14.78 ± 2.15 c	71.0	12.28 ± 0.72 b	71.8	3.01 ± 0.58 b	71.8	2.03 ± 0.03 b	70.6
F-value	61.26		65.99		23.98		40.42	
P-value	<0.001		<0.001		0.002		<0.001	
Cv (%)	10.74		10.59		16.19		12.85	

Percentage reduction was calculated relative to the uninfested control treatment within each planting season. Means followed by the same letter within a column are not significantly different (Tukey's HSD, P > 0.05). F-values are derived from one-way ANOVA. Cv = coefficient of variation. Beetle density refers to the number of adult pairs released per screen cage

Table 4: Relationships between adult *Nisotra dilecta* density and vegetative growth and yield attributes of okra

	r	
Growth and yield parameters	**Early**	**Late**
Number of leaves per plant	-0.910**	-0.870**
Number of branches	-0.812**	-0.718**
Stem diameter	-0.927**	-0.906**
Shoot height	-0.904**	-0.883**

Number of days to 50% flowering	-0.911**	-0.901**
Number of fruits per plant	-0.919**	-0.904**
Fresh fruit weight per plant	-0.892**	-0.919**
Number of seeds per fruit	-0.922**	-0.902**
100-seed weight	-0.795**	-0.884**
Shoot biomass	-0.906**	-0.901**
Fresh fruits yield	-0.875**	-0.886**

Pearson correlation coefficients describing the associations between beetle infestation density and measured crop parameters. ** indicates significance at $P < 0.01$

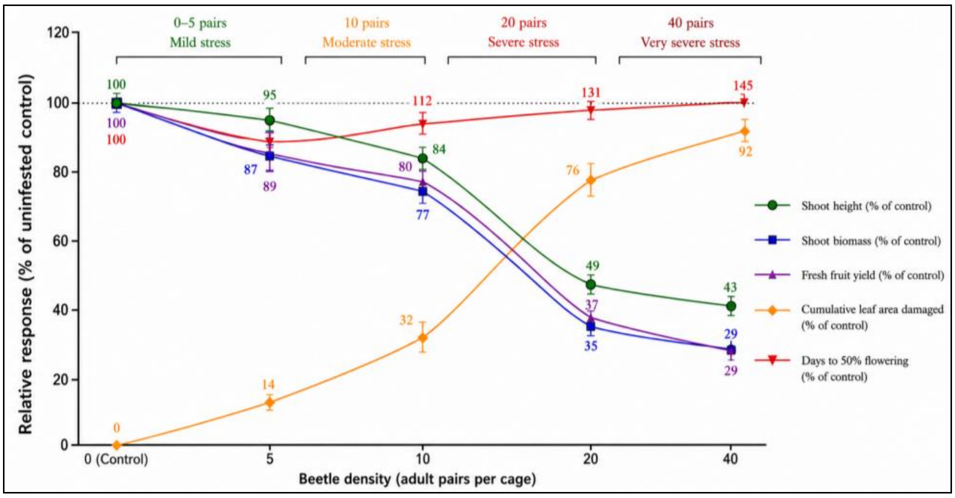

Fig 3: Integrated stress responses of okra to increasing densities of adult *Nisotra dilecta* Dalman

Relative values are expressed as percentages of the uninfested control to facilitate comparison among vegetative growth, leaf damage and yield responses.

Discussion

Okra exhibited a clear threshold response to herbivory by adult *Nisotra dilecta*. Low beetle densities caused relatively minor effects, whereas infestations exceeding 20 adult pairs per cage (8 beetles per plant) resulted in rapid increases in foliar injury and marked reductions in vegetative growth, biomass, flowering, and fruit yield. The consistency of these responses across both planting seasons indicates that infestation intensity, rather than seasonal conditions, was the principal determinant of crop performance and supports the use of threshold-based management strategies.

Increasing beetle density progressively reduced the photosynthetically active leaf area through the characteristic "buckshot" lesions produced during adult feeding. Progressive defoliation decreases whole-plant carbon assimilation by reducing photosynthetically active leaf area, thereby limiting the assimilate supply required to sustain plant growth and reproduction (Wang *et al*., 2021) [16]. Similar reductions in plant productivity following foliar herbivory have been widely attributed to the combined effects of tissue loss and impaired canopy photosynthesis (Züst & Agrawal, 2017; Erb & Reymond, 2019) [18, 5]. Feeding behaviour also changed with infestation density. At low populations, adults fed predominantly on young, fully expanded leaves, whereas higher populations fed indiscriminately across the canopy, suggesting that increased competition broadened resource exploitation and intensified physiological stress. Although visible leaf injury approached saturation during the later stages of crop development, physiological stress continued to increase, indicating that prolonged feeding reduced leaf longevity and photosynthetic efficiency beyond the immediate effects of tissue removal.

The consequences of sustained herbivory became evident in the marked suppression of vegetative growth. Significant reductions in leaf production, branching, stem diameter and shoot height indicate that chronic defoliation limited canopy development and reduced the plant's capacity to intercept light and accumulate assimilates. In addition to direct tissue loss, insect feeding likely activated jasmonate-mediated defence pathways that diverted resources from growth to defence, thereby reinforcing the well-established growth–defence trade-off in plants (Züst & Agrawal, 2017; Erb & Reymond, 2019) [18, 5]. Consequently, increasing beetle density simultaneously reduced photosynthetic capacity and increased metabolic expenditure on defence, resulting in progressive deterioration of plant vigour.

Interestingly, plants infested with only five beetle pairs remained comparable with the control for most vegetative parameters, indicating that okra can tolerate limited herbivory through compensatory mechanisms such as continued leaf production and redistribution of assimilates. Similar compensatory responses have been reported in annual crops exposed to moderate defoliation (Jan *et al*., 2022) [9]. However, once infestation reached 20 and 40 adult pairs, vegetative growth declined sharply, indicating that compensatory mechanisms were no longer sufficient to offset feeding injury. This shift from tolerance to physiological dysfunction clearly illustrates that crop responses to *N. dilecta* are inherently non-linear and governed by biological thresholds rather than proportional increases in insect abundance.

Reproductive development proved even more sensitive than vegetative growth. Delayed flowering under higher infestation densities suggests that sustained herbivory disrupted the carbohydrate supply and hormonal regulation required for reproductive transition. Likewise, significant reductions in fruit number, fresh fruit weight, seed number and seed weight indicate that increasing beetle density impaired both fruit initiation and seed filling. These responses are consistent with the source–sink concept, whereby reduced assimilate production limits the resources available for developing reproductive organs. The strong association between shoot biomass and fruit yield further indicates that reproductive losses resulted primarily from impaired vegetative productivity rather than direct damage to reproductive tissues.

The most important biological implication of this study is the demonstration of a distinct stress threshold. Polynomial regression analyses showed that crop performance remained relatively stable under low beetle densities but declined rapidly once infestations exceeded approximately 10–20 adult pairs per cage. This pattern indicates that okra initially compensates for moderate herbivory through physiological adjustments but becomes increasingly susceptible once feeding pressure exceeds its capacity for recovery. Such threshold responses have been described in other crop–herbivore systems and provide the biological basis for economic threshold concepts in integrated pest management (Pedigo & Rice, 2014) [13]. The present findings extend this concept to *N. dilecta* on okra and provide quantitative evidence that increasing beetle density progressively shifts the crop from a tolerant state to severe physiological stress.

The integrated stress-response analysis further reinforces this interpretation. The strong positive association between beetle density and foliar injury, coupled with the corresponding negative relationships with vegetative growth, biomass accumulation and fruit yield, indicates that these traits constitute integrated components of the plant's physiological response to herbivore stress (Wang *et al.*, 2021; Poelman, 2022) [16, 14]. Consequently, foliar injury provides a practical indicator of cumulative crop stress and may be useful for predicting subsequent yield reductions before irreversible economic losses occur.

The findings generally agree with previous reports identifying flea beetles as among the most destructive foliar pests of okra and related malvaceous crops (Adesina *et al.*, 2018; Ekoja *et al.*, 2023) [1, 4]. However, unlike earlier studies that largely documented pest injury or assessed insecticide efficacy, the present investigation quantified crop responses across a gradient of infestation densities over two planting seasons. This approach provides a more realistic understanding of crop tolerance because it demonstrates that the relationship between herbivory and yield loss is governed by threshold responses rather than a simple linear increase in damage. The consistency of this response across seasons further suggests that the observed threshold is an intrinsic feature of the *N. dilecta*–okra interaction rather than a consequence of seasonal environmental variation.

Another important strength of this study is the integration of temporal leaf damage, vegetative growth, flowering behaviour, biomass accumulation and yield into a single assessment of herbivore-induced stress. The strong relationships among these variables demonstrate that *N. dilecta* influences the entire crop growth cycle, from canopy establishment to reproductive development. This integrated approach provides a more comprehensive understanding of the mechanisms through which increasing herbivore pressure translates into economic loss than studies based solely on yield reduction.

From a practical perspective, these findings have important implications for integrated pest management. The relatively small effects of low beetle populations indicate that the mere presence of adult *N. dilecta* should not automatically trigger insecticide application. Conversely, delaying intervention until infestations become severe can result in substantial and largely irreversible yield losses. Management decisions should therefore be based on pest density and anticipated crop response rather than insect presence alone (Pedigo & Rice, 2014) [13]. Although this study was conducted under controlled screen-house conditions and did not establish formal economic injury levels, the identified threshold responses provide a valuable biological basis for developing field-based action thresholds. Routine monitoring during the early vegetative stage, when plants are most susceptible to defoliation, would enable timely interventions, reduce unnecessary insecticide use and promote more sustainable pest management.

A limitation of this study is that it was conducted under controlled screen-house conditions where environmental variability and beetle dispersal were restricted. Field conditions may modify crop responses through interactions with weather, soil fertility, natural enemies and other biotic or abiotic factors. Consequently, validation of the identified threshold responses under field conditions and across different agroecological zones is required. Further studies should also evaluate varietal differences in tolerance and resistance to strengthen the development of integrated management strategies.

Conclusion

Increasing densities of adult *Nisotra dilecta* induced progressive, density-dependent stress in okra, leading to greater foliar injury, reduced vegetative growth, delayed flowering, and significant losses in biomass and fruit yield. Okra tolerated low infestation levels but exhibited rapid declines in performance once beetle populations exceeded 20 adult pairs per cage. These findings establish a biological basis for threshold-based management of *N. dilecta* in okra. Regular monitoring of *N. dilecta* populations, particularly during the early vegetative stage, is recommended to prevent infestations from exceeding damaging threshold levels. Future studies should validate these thresholds under field conditions, determine economic injury and action thresholds, assess varietal tolerance and resistance, and integrate these findings with biological control, cultural practices, and selective insecticide use to support sustainable integrated pest management.

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