



Research Article

Bund Refugia Alter Arthropod Functional Guild Structure in Lowland Rice (*Oryza sativa* L.): Evidence from Diversity, Evenness and Dominance Indices

Bund Refugia Mengubah Struktur Gilda Fungsional Artropoda di Lahan Sawah (*Oryza sativa* L.): Bukti dari Indeks Keanekaragaman, Kemerataan, dan Dominansi

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ABSTRACT

Vegetation retained on earthen bunds of irrigated rice fields supplies shelter, pollen, nectar and alternative hosts, yet consequences for the arthropod community inside the crop remain unevenly documented. A randomised complete block design with three bund treatments and three replicates was used to quantify arthropod assemblages in transplanted lowland rice across nine weekly samplings (14–70 days after transplanting; DAT). Treatments were cleared bunds (T_0), bunds under spontaneous vegetation (*Portulaca oleracea*, *Cyperus iria*, *Cyperus rotundus*, *Eleusine indica*; T_1), and bunds sown with sesame (*Sesamum indicum*) and mungbean (*Vigna radiata*; T_2). Twenty-seven arthropod taxa in 20 families and 7 orders were recorded (232 individuals). Herbivore relative abundance declined from 11.90% (T_0) to 6.85% (T_1) and 5.33% (T_2), while parasitoid relative abundance rose from 14.29% to 20.55% and 30.67%, lifting the natural-enemy-to-herbivore ratio from 6.00 to 10.40 and 12.75. Shannon diversity peaked at the sixth sampling and fell to zero from 63 DAT onward; seasonal means were 0.93, 0.99 and 1.13. Because indices were computed from pooled catch, the analysis of variance is descriptive: sampling occasion dominated variability whereas bund vegetation explained little (partial $\eta^2 = 0.09$ –0.20), with treatment confidence intervals overlapping for every index. Evenness and Simpson dominance remained low across all treatments. A composite decision-support heuristic ranked T_2 first (100.0), ahead of T_1 (49.9) and T_0 (2.3), identifying sesame–mungbean bund refugia as the most promising option for further testing.

KEYWORDS: conservation biological control; *Cyrtorhinus lividipennis*; ecological engineering; parasitoid guild; *Sesamum indicum*; *Vigna radiata*.

ABSTRAK

Vegetasi yang dipertahankan pada pematang sawah irigasi menyediakan tempat berlindung, serbuk sari, nektar, dan inang alternatif, namun dampaknya terhadap komunitas artropoda di dalam pertanaman masih belum terdokumentasi secara merata. Rancangan acak kelompok lengkap dengan tiga perlakuan pematang dan tiga ulangan digunakan untuk mengkuantifikasi kumpulan artropoda pada padi sawah transplantasi selama sembilan pengambilan sampel mingguan (14–70 hari setelah tanam; HST). Perlakuan meliputi pematang yang dibersihkan (T_0), pematang yang dibiarkan ditumbuhi vegetasi spontan dominan (*Portulaca oleracea*, *Cyperus iria*, *Cyperus rotundus*, *Eleusine indica*; T_1), serta pematang yang ditanami wijen (*Sesamum indicum*) dan kacang hijau (*Vigna radiata*; T_2). Dua puluh tujuh taksa artropoda dalam 20 famili dan 7 ordo tercatat (232 individu). Kelimpahan relatif herbivor menurun dari 11,90% (T_0) menjadi 6,85% (T_1) dan 5,33% (T_2), sementara kelimpahan relatif parasitoid meningkat dari 14,29% menjadi 20,55% dan 30,67%, sehingga rasio musuh alami terhadap herbivor meningkat dari 6,00 menjadi 10,40 dan 12,75. Indeks Shannon mencapai puncak pada pengambilan sampel keenam dan turun menjadi nol mulai 63 HST; rata-rata musiman berturut-turut adalah 0,93, 0,99, dan 1,13. Karena indeks dihitung dari tangkapan tergabung, analisis ragam bersifat deskriptif: kesempatan pengambilan sampel mendominasi variabilitas, sedangkan vegetasi pematang menjelaskan sedikit variasi (η^2 parsial = 0,09–0,20), dengan selang kepercayaan antarperlakuan yang tumpang tindih untuk setiap indeks. Kemerataan dan dominansi Simpson tetap rendah di semua perlakuan. Heuristik dukungan keputusan komposit menempatkan T_2 di peringkat pertama (100,0), diikuti T_1 (49,9) dan T_0 (2,3), mengidentifikasi refugia pematang wijen–kacang hijau sebagai pilihan yang paling menjanjikan untuk pengujian lebih lanjut.

KATA KUNCI: *Cyrtorhinus lividipennis*; gilda parasitoid; pengendalian hayati konservasi; rekayasa ekologi; *Sesamum indicum*; *Vigna radiata*.

INTRODUCTION

Irrigated rice feeds more than half of humanity, and the arthropod fauna that inhabits it is among the most

intensively studied of any cropping system. Decades of work have shown that the crop supports a food web of unusual depth for an annual monoculture, with

herbivores, predators, parasitoids and aquatic detritivores coexisting across a growing season of roughly one hundred days (Wang et al., 2024). What sustains that food web is less obvious than it first appears. Rice itself offers neither pollen accessible to small wasps nor nectar, and the flooded field is hostile to many ground-dwelling predators during land preparation. The resources that carry natural enemies through those bottlenecks come largely from outside the crop, from the bunds, ditch banks and fallow patches that surround it (Horgan et al., 2022).

Insecticide-centred management has repeatedly undermined this arrangement. Broad-spectrum applications kill predators and parasitoids disproportionately, and planthopper resurgence after spraying is one of the best-documented failures in tropical crop protection. Even sublethal exposure alters parasitoid searching behaviour and handling time, with consequences that propagate across several generations (Ray et al., 2023). Against this background, conservation biological control has moved from an attractive principle to an operational programme. Its logic is straightforward: if the limiting factor for natural enemies is the supply of non-prey food and refuge, then supplying those resources near the crop should raise enemy pressure on pests (Colazza et al., 2023).

Floral resources are the central currency in that exchange. Nectar sugars extend adult parasitoid longevity and raise lifetime fecundity, and pollen supports omnivorous predators during periods of prey scarcity (Herz et al., 2021). Trait-based evidence indicates that attractiveness, corolla architecture and flowering phenology jointly filter which natural enemies actually gain from a given planting, so species choice governs the size of the benefit (Gurr et al., 2024). Sugar need not come from flowers alone; honeydew excreted by planthoppers and leafhoppers also feeds egg parasitoids, and its composition shifts with host plant genotype and nitrogen supply, modulating parasitism independently of any sown resource (Peñalver-Cruz & Horgan, 2022).

In rice specifically, the earthen bund has become the preferred platform for such interventions because it occupies land already withdrawn from production. Diversified bund vegetation raises predator density and advances early-season pest suppression in subtropical paddies (Qian et al., 2021), and eco-engineered bunds planted with nectar-rich species have reduced brown planthopper populations while maintaining grain yield in South Asia (Yele et al., 2023). Field trials against leafhopper vectors of tungro reached the same conclusion in Southeast Asian lowland rice, with natural enemy abundance highest in eco-engineered plots at later crop stages (Rosida et al., 2025). Augmentative releases of egg parasitoids integrate well with these habitat measures, since released wasps survive longer where floral subsidies exist (Babendreier et al., 2022), and release efficacy itself depends on rearing history and post-release nutrition (Basana Gowda et al., 2021). Benefits also scale upward: landscapes retaining semi-natural

elements show stronger natural pest suppression than simplified ones (Ali et al., 2023), and modelling across European farmland indicates that landscape features can partly compensate for reduced pesticide use without eroding farm income (Klinnert et al., 2024). Where insecticide inputs persist, however, these gains are readily reversed (Ray et al., 2023).

Two gaps persist. First, most eco-engineering trials compare an elaborate sown mixture against a bare control, which conflates the effect of flowering resources with the effect of vegetation per se; the spontaneous weed flora already present on untended bunds is rarely treated as a treatment in its own right, even though it may host parasitoids at no cost to the farmer. Second, evaluation usually stops at abundance counts, so it remains unclear whether refugia shift community structure or merely add individuals. Diversity, evenness and dominance indices address that question directly, and agricultural diversification syntheses emphasise that implementation details determine whether ecosystem-service gains materialise at all (Seimandi-Corda et al., 2026). Resolving the distinction matters practically, because bund management is one of the few interventions a smallholder can adopt without additional land, equipment or recurrent cost, and because the composition of the enemy complex, rather than its total size, determines which pest guilds are regulated (Horgan et al., 2022).

This study therefore compared three bund conditions, cleared, spontaneously vegetated, and sown with sesame and mungbean, in a transplanted lowland rice field, and tracked the arthropod assemblage weekly from early tillering to maturity. The objectives were to characterise taxonomic composition and trophic roles under each bund condition, to test whether bund vegetation altered Shannon diversity, evenness and Simpson dominance once seasonal variation was accounted for, and to rank the three conditions objectively against a composite of community-level criteria.

MATERIALS AND METHODS

Study Site and Period

The experiment was conducted in a farmer-managed block of transplanted puddled lowland rice over one complete crop cycle, from transplanting to harvest. The site is representative of continuously irrigated lowland rice in the humid tropics, where fields are separated by earthen bunds approximately 0.4 m wide and 0.3 m high that carry spontaneous herbaceous vegetation whenever they are left untended.

Materials and Experimental Design

The experiment was laid out as a randomised complete block design with three treatments and three replicates, giving nine experimental units. Blocks were positioned perpendicular to the irrigation gradient so that water supply was homogeneous within each block. Each experimental unit consisted of a transplanted rice plot together with the earthen bund enclosing it, and plots were separated by sufficient distance to limit movement of arthropods between adjacent treatments.

Three treatments were defined by the vegetation maintained on the bunds. T_0 comprised bunds kept clear of all vegetation by regular manual weeding and served as the control. T_1 comprised bunds left under the dominant spontaneous flora of the site, namely *Portulaca oleracea* L., *Cyperus iria* L., *Cyperus rotundus* L. and *Eleusine indica* (L.) Gaertn. T_2 comprised bunds sown with the companion species sesame (*Sesamum indicum* L.) and mungbean (*Vigna radiata* (L.) R. Wilczek). Sesame and mungbean were direct-sown on the bund crowns at the time of final land preparation so that flowering coincided with the vegetative phase of the rice crop.

Certified seed of a high-yielding inbred lowland indica rice cultivar was used throughout. Land was prepared with a mouldboard plough and levelled; farmyard manure was incorporated at 150 kg ha^{-1} during the final tillage operation. Twenty-five-day-old seedlings were transplanted at two to three seedlings per hill in a clustered row arrangement of 4:1, with spacing of $40 \text{ cm} \times 20 \text{ cm} \times 10 \text{ cm}$. Mineral fertiliser rates followed a soil-test recommendation and comprised urea at 150 kg ha^{-1} and muriate of potash at 100 kg ha^{-1} . Each fertiliser was split into three equal applications: one-third broadcast and trampled into the puddled surface immediately before transplanting, one-third at two weeks after transplanting, and the remaining third at six weeks after transplanting. No insecticide, herbicide or fungicide was applied to any plot at any stage, so that arthropod assemblages reflected bund treatment rather than pesticide selection.

Data Collection and Statistical Analysis

Sampling began when the crop was 14 days after transplanting (DAT) and continued at seven-day intervals until one week before harvest, giving nine sampling occasions (S_1 – S_9) spanning 14 to 70 DAT. On each occasion, arthropods were recorded from the rice canopy, from the sown bund refugia and from the spontaneous bund flora within each experimental unit, using direct visual counts supplemented by sweep netting along fixed transects of equal length. Within every experimental unit the rice canopy and the bund surface were treated as two separate strata, the canopy stratum combining sweep netting along a diagonal transect with visual inspection of randomly selected hills, and the bund stratum combining sweep netting along the bund crown with visual inspection of the bund vegetation. All specimens were preserved in 70% ethanol and transferred to the laboratory, where they were identified to the lowest practicable taxonomic level by comparing morphological characters against standard illustrated keys and descriptions for rice insect pests and their arthropod parasites and predators. Each taxon was then assigned to one of four functional guilds, herbivore, predator, parasitoid or detritivore, on the basis of published feeding biology for the genus or family concerned.

Four community descriptors were computed for every treatment on every sampling occasion. Relative abundance (RA) of a taxon was calculated as the number of individuals of that taxon divided by the total number of individuals recorded, expressed as a

percentage. The Shannon diversity index was computed as $H' = -\sum p_i \ln p_i$, where p_i is the proportional abundance of the i -th taxon. Diversity was classified as low for $H' < 1.0$, moderate for $1.0 < H' \leq 3.0$, and high for $H' > 3.0$. The evenness index was computed as $E = H' / \ln S$, where S is the number of taxa recorded, and classified as low for $0 < E \leq 0.50$, moderate for $0.50 < E \leq 0.75$, and high for $0.75 < E \leq 1.00$. Simpson's dominance index was computed as $C = \sum p_i^2$, with $0 < C \leq 0.5$ indicating that no taxon dominated the assemblage and $0.5 < C \leq 1.0$ indicating the presence of a dominant taxon.

Relative abundance, H' , E and C were computed from the catch pooled across the three replicate plots of a treatment, which yields one value per treatment per sampling occasion rather than one value per plot. The diversity indices are therefore not replicated at the level of the experimental unit, and an analysis of variance built on them has an error term that expresses occasion-to-occasion variation rather than independent replication of the diversity estimate. The diversity analysis of variance is accordingly presented as a descriptive partition of variability and carries no inferential weight; inferential statements are confined to the guild abundance data, for which genuine plot-level replication exists, and to the regression of H' on crop age, where sampling occasion is the unit of observation.

Shannon diversity, evenness and Simpson dominance were partitioned by analysis of variance appropriate to the randomised complete block design, with bund vegetation as the treatment factor and sampling occasion as the blocking factor, yielding 2, 8 and 16 degrees of freedom for treatment, block and error respectively. Treatment means were separated with the least significant difference at the 5% probability level, and the coefficient of variation was reported for each response. Partial eta squared was computed for each source as $SS_{\text{source}} / (SS_{\text{source}} + SS_{\text{error}})$ and 95% confidence intervals were placed on treatment means as $m \pm t_{0.025, 16} \times \sqrt{(MSE/9)}$, so that the practical magnitude of treatment differences can be judged independently of any p-value. Sampling adequacy was assessed by individual-based (Hurlbert) rarefaction of the pooled seasonal catch of each treatment, with richness compared at the smallest common sample of 73 individuals, and by the bias-corrected Chao1 richness estimator; sample completeness was expressed as observed richness divided by Chao1.

A Pearson correlation matrix was computed among H' , E and C because three continuous response variables were measured; the matrix was restricted to the eighteen treatment-by-occasion combinations on which arthropods were actually recorded, since occasions returning no individuals force all three indices to zero simultaneously and would generate spurious association, and significance was judged against critical values of r for 16 degrees of freedom. Quadratic regression was fitted separately for each treatment and for the pooled data to describe the response of H' to days after transplanting, because sampling date is a quantitative factor; the fitted

equation, coefficient of determination, F statistic, probability and the predicted optimum were reported. A composite ranking was then constructed across seven community criteria to identify the best-performing bund condition objectively, since no single index integrates taxonomic and functional responses. Principal component analysis was not performed, because only three continuous response variables were measured, which is below the threshold at which ordination conveys information beyond the correlation matrix itself. All computations were carried out at $\alpha = 0.05$ in R version 4.4.1 (R Core Team, Vienna, Austria).

RESULTS

Analysis of variance, reported as a descriptive partition of variability rather than as an inferential test, separated the two sources of variation sharply (Table 1). Sampling occasion was associated with $p < 0.01$ for H' and E and with $p < 0.05$ for C , and accounted for most of the variability not attributable to treatment (partial $\eta^2 = 0.89, 0.97$ and 0.57 respectively). Bund vegetation reached no conventional significance threshold for any index and accounted for little variability, with partial η^2 of 0.09 for H' , 0.20 for E and 0.10 for C .

Table 1. Analysis of variance for Shannon diversity (H'), evenness (E) and Simpson dominance (C) of arthropod assemblages in rice under three bund vegetation treatments.

Response	Source of variation	df	Significance	Partial η^2
H'	Sampling occasion (block)	8	**	0.886
	Bund vegetation	2	ns	0.088
	Error	16		
	Total	26		
E	Sampling occasion (block)	8	**	0.966
	Bund vegetation	2	ns	0.198
	Error	16		
	Total	26		
C	Sampling occasion (block)	8	*	0.568
	Bund vegetation	2	ns	0.105
	Error	16		
	Total	26		

Note: ** = $p < 0.01$; * = $p < 0.05$; ns = not significant. H' , Shannon diversity index; E , evenness index; C , Simpson dominance index; df , degrees of freedom. Partial $\eta^2 = SS_{\text{source}} / (SS_{\text{source}} + SS_{\text{error}})$.

A total of 232 individuals representing 27 taxa, 20 families and 7 orders was recorded across the three treatments (Tables 2, 3 and 4). Nineteen taxa and 84 individuals occurred under cleared bunds, 20 taxa and 73 individuals under spontaneous bund vegetation, and 21 taxa and 75 individuals under sesame and mungbean. *Cyrtorhinus lividipennis* was the most

abundant single taxon in T_0 and T_1 , with 25 and 18 individuals, while *Chironomus* sp. A and *Trichogramma* sp. were the most abundant taxa in T_2 , with 11 and 10 individuals. *Paederus fuscipes* occurred only in T_2 , *Rogas narangae* only in T_1 , and *Scirpophaga innotata* and *Empoasca* sp. only in T_0 .

Table 2. Taxa, functional roles and abundance of arthropods recorded in rice with cleared bunds (T_0).

Functional role	Order	Family	Taxon	Individuals
Herbivore	Diptera	Agromyzidae	<i>Agromyza oryzae</i> Munakata	1
	Hemiptera	Cicadellidae	<i>Cicadulina bipunctata</i> (Melichar)	1
	Hemiptera	Cicadellidae	<i>Empoasca</i> sp.	1
	Hemiptera	Delphacidae	<i>Nilaparvata lugens</i> (Stål)	5
	Lepidoptera	Pyalidae	<i>Scirpophaga innotata</i> (Walker)	2
Predator	Araneae	Araneidae	<i>Gea</i> sp.	5
	Araneae	Clubionidae	<i>Cheiracanthium</i> sp. A	5
	Araneae	Thomisidae	<i>Misumena</i> sp.	3
	Araneae	Thomisidae	<i>Regillus</i> sp. B	9
	Coleoptera	Coccinellidae	<i>Menochilus sexmaculatus</i> (Fabricius)	1
	Hemiptera	Miridae	<i>Cyrtorhinus lividipennis</i> Reuter	25
	Hymenoptera	Ceraphronidae	<i>Ceraphron</i> sp. B	1
Parasitoid	Hymenoptera	Scelionidae	<i>Telenomus remus</i> Nixon	1
	Hymenoptera	Scelionidae	<i>Telenomus</i> sp. A	1
	Hymenoptera	Scelionidae	<i>Telenomus</i> sp. B	4
	Hymenoptera	Trichogrammatidae	<i>Trichogramma</i> sp.	5

Functional role	Order	Family	Taxon	Individuals
Detritivore	Diptera	Chironomidae	<i>Chironomus</i> sp. A	7
	Diptera	Chironomidae	<i>Chironomus</i> sp. B	2
	Diptera	Phoridae	<i>Megaselia scalaris</i> (Loew)	5
Total			19 taxa	84

Note: T_0 , bunds kept clear of vegetation.

Table 3. Taxa, functional roles and abundance of arthropods recorded in rice with bunds under spontaneous vegetation (T_1).

Functional role	Order	Family	Taxon	Individuals
Herbivore	Diptera	Ephydriidae	<i>Hydrellia griseola</i> (Fallén)	1
	Hemiptera	Delphacidae	<i>Nilaparvata lugens</i> (Stål)	3
	Hemiptera	Cicadellidae	<i>Cicadulina bipunctata</i> (Melichar)	1
Predator	Araneae	Araneidae	<i>Gea</i> sp.	5
	Araneae	Clubionidae	<i>Cheiracanthium</i> sp. A	5
	Araneae	Thomisidae	<i>Misumena</i> sp.	1
	Araneae	Thomisidae	<i>Regillus</i> sp. B	5
	Coleoptera	Anthicidae	<i>Formicomus</i> sp.	1
	Coleoptera	Coccinellidae	<i>Micraspis inops</i> Mulsant	2
	Hemiptera	Miridae	<i>Cyrtorhinus lividipennis</i> Reuter	18
Parasitoid	Strepsiptera	Halictophagidae	<i>Elenchus yasumatsui</i> Kifune & Hirashima	1
	Hymenoptera	Braconidae	<i>Rogas narangae</i> Rohwer	2
	Hymenoptera	Ceraphronidae	<i>Ceraphron</i> sp. B	1
	Hymenoptera	Eulophidae	<i>Tetrastichus</i> sp.	1
	Hymenoptera	Scelionidae	<i>Telenomus remus</i> Nixon	1
	Hymenoptera	Scelionidae	<i>Telenomus</i> sp. B	4
	Hymenoptera	Trichogrammatidae	<i>Trichogramma</i> sp.	5
Detritivore	Diptera	Chironomidae	<i>Chironomus</i> sp. A	5
	Diptera	Chironomidae	<i>Chironomus</i> sp. B	4
	Diptera	Phoridae	<i>Megaselia scalaris</i> (Loew)	7
Total			20 taxa	73

Note: T_1 , bunds left under dominant spontaneous vegetation (*Portulaca oleracea*, *Cyperus iria*, *Cyperus rotundus*, *Eleusine indica*).

Table 4. Taxa, functional roles and abundance of arthropods recorded in rice with bunds sown to sesame and mungbean (T_2).

Functional role	Order	Family	Taxon	Individuals
Herbivore	Diptera	Ephydriidae	<i>Hydrellia griseola</i> (Fallén)	1
	Hemiptera	Delphacidae	<i>Nilaparvata lugens</i> (Stål)	3
Predator	Araneae	Araneidae	<i>Gea</i> sp.	7
	Araneae	Clubionidae	<i>Cheiracanthium</i> sp. A	3
	Araneae	Thomisidae	<i>Misumena</i> sp.	2
	Araneae	Thomisidae	<i>Regillus</i> sp. B	5
	Coleoptera	Anthicidae	<i>Formicomus</i> sp.	1
	Coleoptera	Coccinellidae	<i>Menochilus sexmaculatus</i> (Fabricius)	1
	Coleoptera	Coccinellidae	<i>Micraspis inops</i> Mulsant	1
	Coleoptera	Staphylinidae	<i>Paederus fuscipes</i> Curtis	3
	Hemiptera	Miridae	<i>Cyrtorhinus lividipennis</i> Reuter	5
Parasitoid	Strepsiptera	Halictophagidae	<i>Elenchus yasumatsui</i> Kifune & Hirashima	1
	Hymenoptera	Eulophidae	<i>Tetrastichus</i> sp.	1
	Hymenoptera	Eulophidae	<i>Tetrastichus howardi</i> (Olliff)	2
	Hymenoptera	Scelionidae	<i>Telenomus remus</i> Nixon	1
	Hymenoptera	Scelionidae	<i>Telenomus</i> sp. A	3
	Hymenoptera	Scelionidae	<i>Telenomus</i> sp. B	5
	Hymenoptera	Trichogrammatidae	<i>Trichogramma</i> sp.	10
Detritivore	Diptera	Chironomidae	<i>Chironomus</i> sp. A	11

Functional role	Order	Family	Taxon	Individuals
	Diptera	Chironomidae	<i>Chironomus</i> sp. B	3
	Diptera	Phoridae	<i>Megaselia scalaris</i> (Loew)	6
Total			21 taxa	75

Note: T_2 , bunds sown with sesame (*Sesamum indicum*) and mungbean (*Vigna radiata*).

Guild structure differed among the three bund conditions (Table 5). Herbivore individuals numbered 10, 5 and 4 in T_0 , T_1 and T_2 , corresponding to relative abundances of 11.90%, 6.85% and 5.33%. Parasitoid individuals numbered 12, 15 and 23, corresponding to 14.29%, 20.55% and 30.67%. Predator relative abundance moved in the opposite direction, from 57.14% in T_0 to 50.68% in T_1 and 37.33% in T_2 , while

detritivore relative abundance rose from 16.67% to 21.92% and 26.67%. Herbivore richness fell from five taxa to three and then two, predator richness rose from six to seven and then nine, and parasitoid richness rose from five to seven in both vegetated treatments. The natural-enemy-to-herbivore ratio was 6.00, 10.40 and 12.75 for T_0 , T_1 and T_2 .

Table 5. Guild abundance, relative abundance and taxonomic richness of arthropod assemblages under three bund vegetation treatments.

Attribute	T_0	T_1	T_2
Herbivore individuals	10	5	4
Predator individuals	48	37	28
Parasitoid individuals	12	15	23
Detritivore individuals	14	16	20
Total individuals	84	73	75
Herbivore relative abundance (%)	11.90	6.85	5.33
Predator relative abundance (%)	57.14	50.68	37.33
Parasitoid relative abundance (%)	14.29	20.55	30.67
Detritivore relative abundance (%)	16.67	21.92	26.67
Herbivore taxa	5	3	2
Predator taxa	6	7	9
Parasitoid taxa	5	7	7
Detritivore taxa	3	3	3
Total taxa	19	20	21
Natural enemy : herbivore ratio	6.00	10.40	12.75

Note: T_0 , cleared bunds; T_1 , spontaneous bund vegetation; T_2 , bunds sown with sesame and mungbean. Natural enemies comprise predators and parasitoids combined.

Rarefaction of the pooled seasonal catch showed that observed richness was still rising with sampling effort in all three treatments (Table 6; Supplementary Figure S1). Standardised to the smallest common sample of 73 individuals, expected richness was 18.05 taxa in T_0 , 20.00 in T_1 and 20.81 in T_2 , preserving the rank order

of the raw counts. Chao1 estimated 26.0, 29.3 and 28.0 taxa respectively, corresponding to sample completeness of 73.1%, 68.2% and 75.0%. Seven to eight taxa were represented by a single individual in each treatment and two by exactly two individuals.

Table 6. Sampling adequacy of the arthropod assemblages under three bund vegetation treatments.

Treatment	Individuals	Observed taxa	$E[S]$ at $n = 73$	Singletons (f_1)	Doubletons (f_2)	Chao1	Completeness (%)
T_0	84	19	18.05	7	2	26.0	73.1
T_1	73	20	20.00	8	2	29.3	68.2
T_2	75	21	20.81	7	2	28.0	75.0

Note: $E[S]$ at $n = 73$, expected taxon richness after individual-based (Hurlbert) rarefaction to the smallest common sample; Chao1, bias-corrected Chao1 richness estimator; completeness, observed richness expressed as a percentage of Chao1. T_0 , cleared bunds; T_1 , spontaneous bund vegetation; T_2 , bunds sown with sesame and mungbean.

The seasonal profile of the three indices is given in Table 7. No arthropods were recorded at S_1 , and none at S_8 or S_9 , so all three indices took the value zero on those occasions in every treatment. The absence of catch at S_1 coincided with a canopy still too sparse at 14 DAT to retain foliage-dwelling arthropods or to yield material by sweep netting, while the absence from S_8 onward followed terminal field drainage and

the onset of leaf senescence, which removed standing water, prey and shelter during grain filling and ripening. Between S_2 and S_7 , H' ranged from 0.54 to 2.01 in T_0 , from 0.76 to 2.10 in T_1 , and from 1.04 to 2.20 in T_2 . Maximum H' occurred at S_6 in T_0 (2.01), T_1 (2.02) and T_2 (2.20), with the single highest value in T_1 of 2.10 recorded at S_5 . Evenness remained between 0.19 and 0.37 in T_0 , between 0.19 and 0.35 in T_1 , and between

0.22 and 0.35 in T_2 . Simpson dominance reached 0.89 in T_0 at S_5 and 0.66 in T_1 at S_4 ; all other non-zero values fell below 0.52.

Table 7. Shannon diversity (H'), evenness (E) and Simpson dominance (C) of arthropod assemblages across nine sampling occasions.

Index	Treatment	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9
H'	T_0	0	1.27	1.87	1.56	0.54	2.01	1.10	0	0
	T_1	0	1.03	1.60	0.76	2.10	2.02	1.39	0	0
	T_2	0	1.84	1.86	1.50	1.73	2.20	1.04	0	0
E	T_0	0	0.21	0.19	0.31	0.27	0.34	0.37	0	0
	T_1	0	0.21	0.20	0.19	0.23	0.25	0.35	0	0
	T_2	0	0.26	0.23	0.25	0.29	0.22	0.35	0	0
C	T_0	0	0.32	0.15	0.22	0.89	0.17	0.22	0	0
	T_1	0	0.52	0.41	0.66	0.14	0.14	0.25	0	0
	T_2	0	0.17	0.21	0.28	0.19	0.12	0.19	0	0

Note: Sampling occasions S_1 – S_9 correspond to 14, 21, 28, 35, 42, 49, 56, 63 and 70 days after transplanting. T_0 , cleared bunds; T_1 , spontaneous bund vegetation; T_2 , bunds sown with sesame and mungbean.

Seasonal mean values are summarised in Table 8. Means were 0.93, 0.99 and 1.13 for H' , 0.19, 0.16 and 0.18 for E , and 0.22, 0.24 and 0.13 for C in T_0 , T_1 and T_2 respectively. Differences among treatment means did not exceed the least significant difference at the 5%

level for any index, and the 95% confidence intervals of the three treatment means overlapped for H' , for E and for C . The coefficient of variation was 35.0% for H' , 18.0% for E and 91.6% for C .

Table 8. Seasonal mean values of the three community indices with least significant difference and coefficient of variation.

Treatment	Mean H'	95% CI of H'	Mean E	95% CI of E	Mean C	95% CI of C
T_0	0.93a	0.68–1.18	0.19a	0.17–0.21	0.22a	0.09–0.35
T_1	0.99a	0.74–1.24	0.16a	0.14–0.18	0.24a	0.11–0.36
T_2	1.13a	0.88–1.38	0.18a	0.16–0.20	0.13a	0.00–0.26
LSD (0.05)	0.355		0.031		0.178	
CV (%)	35.0		18.0		91.6	

Note: Means in the same column followed by the same letter do not differ significantly (LSD, $p < 0.05$). LSD, least significant difference; CV, coefficient of variation. Confidence intervals were computed as $m \pm t_{0.025,16} \times \sqrt{(MSE/9)}$ and overlap across all three treatments for every index. H' , Shannon diversity index; E , evenness index; C , Simpson dominance index.

Correlation analysis restricted to the eighteen occasions on which arthropods were present returned a strong negative association between H' and C (Table

9; $r = -0.811$, $p < 0.01$). Neither H' and E ($r = -0.128$) nor E and C ($r = -0.246$) were significantly correlated.

Table 9. Pearson correlation matrix among arthropod community indices across the eighteen treatment-by-occasion combinations on which arthropods were recorded.

	H'	E	C
H'	1.000		
E	-0.128 ns	1.000	
C	-0.811 **	-0.246 ns	1.000

Note: ** = $p < 0.01$; ns = not significant (as defined for Table 1); $n = 18$. Critical $r = 0.468$ at $p = 0.05$ and 0.590 at $p = 0.01$ for 16 degrees of freedom. H' , Shannon diversity index; E , evenness index; C , Simpson dominance index.

Quadratic models fitted to the relationship between H' and days after transplanting explained 57.9%, 71.1% and 75.0% of the variation in T_0 , T_1 and T_2 (Table 10). The model was significant for T_1 ($p = 0.0242$) and T_2

($p = 0.0156$) but not for T_0 ($p = 0.0746$). Predicted optima fell at 38.9, 40.9 and 38.8 DAT, and the pooled model placed the optimum at 39.6 DAT with $R^2 = 0.664$ and $p < 0.0001$.

Table 10. Quadratic regression of Shannon diversity on days after transplanting (D).

Treatment	Fitted equation	R^2	F-value	p-value	Predicted optimum (DAT)
T_0	$H' = -1.3238 + 0.1486D - 0.001907D^2$	0.579	4.13	0.0746	38.9
T_1	$H' = -2.1502 + 0.1912D - 0.002341D^2$	0.711	7.37	0.0242	40.9
T_2	$H' = -1.6469 + 0.1847D - 0.002381D^2$	0.750	9.01	0.0156	38.8

Treatment	Fitted equation	R ²	F-value	p-value	Predicted optimum (DAT)
Pooled	$H' = -1.7070 + 0.1748D - 0.002210D^2$	0.664	23.70	<0.0001	39.6

Note: *D*, days after transplanting (DAT), as defined for Table 7; *R*², coefficient of determination; *H'*, Shannon diversity index. Predicted optimum is the vertex of the fitted quadratic.

Composite ranking across the seven criteria placed *T*₂ first with an index of 100.0, *T*₁ second with 49.9, and *T*₀ third with 2.3 (Table 11). *T*₂ held the most favourable value for all seven criteria, *T*₁ held the most favourable value for parasitoid richness only, and *T*₀ held the most favourable value for none. The index is a decision-support heuristic for comparing bund

options on a single scale and is not a statistical test; because every criterion is rescaled so that the best and worst treatments occupy the endpoints, a small and statistically unsupported difference is expanded to the full range exactly as a large one would be, and the resulting scores should be read as an ordering rather than as a measure of effect size.

Table 11. Composite ranking of bund vegetation treatments across seven community criteria.

Criterion	<i>T</i> ₀	<i>T</i> ₁	<i>T</i> ₂
Mean Shannon diversity	0.00	0.30	1.00
Total taxonomic richness	0.00	0.50	1.00
Parasitoid abundance	0.00	0.27	1.00
Parasitoid richness	0.00	1.00	1.00
Natural enemy : herbivore ratio	0.00	0.65	1.00
Low Simpson dominance	0.16	0.00	1.00
Low herbivore relative abundance	0.00	0.77	1.00
Composite index	2.3	49.9	100.0
Rank	3	2	1

Note: Each criterion was rescaled to a 0–1 range across treatments, with 1 assigned to the most favourable value for conservation biological control (highest diversity, richness, parasitoid abundance, parasitoid richness and natural-enemy-to-herbivore ratio; lowest Simpson dominance and lowest herbivore relative abundance). The composite index is the mean of the seven rescaled scores expressed as a percentage. The index is a decision-support heuristic, not a statistical result; rescaling forces the extreme treatments to 0 and 1 irrespective of the magnitude or significance of the underlying difference.

DISCUSSION

Bund vegetation was associated with a reorganisation of the arthropod assemblage that the aggregate diversity statistics did not register. The descriptive partition in Table 1 attributes almost nothing to bund treatment, and the confidence intervals in Table 8 overlap, so the diversity data neither demonstrate nor exclude a treatment effect; what follows interprets the guild composition data, where plot-level replication exists, and treats the index contrasts as patterns to be tested rather than as results. The dissociation still deserves attention, because *H'*, *E* and *C* prove insensitive to precisely the kind of change the treatments appear to have produced. The explanation lies in how these indices are constructed. Shannon diversity weights all taxa by proportional abundance irrespective of trophic role, so a transfer of fifteen individuals from the herbivore and predator pools into the parasitoid and detritivore pools leaves the index largely unmoved while transforming the functional character of the community. Guild-resolved metrics captured what the summary indices could not, a point also emphasised in metabarcoding surveys of paddy parasitoid assemblages, where taxonomic resolution rather than index value carried the ecological signal (Wang et al., 2024).

Herbivore relative abundance halved under spontaneous bund flora and fell by more than half under sown refugia, from 11.90% to 6.85% and 5.33%. Converted into enemy pressure, the natural-enemy-to-

herbivore ratio doubled under refugia. Comparable directional shifts have been reported from eco-engineered paddies in subtropical China, where bund plant diversity correlated positively with predator density and early-season herbivore regulation (Qian et al., 2021), and from lowland trials in South Asia in which oilseed and flowering bund crops delayed brown planthopper appearance and reduced its peak population (Yele et al., 2023). Field experiments in Southeast Asian rice reached the same conclusion for leafhopper vectors of tungro, with natural enemy abundance highest in eco-engineered plots at later crop stages (Rosida et al., 2025). The mechanism common to these systems is resource subsidy rather than direct interference, since bund plants neither shade nor physically obstruct the crop.

Parasitoids responded more strongly than predators, which is consistent with their nutritional biology. Adult Hymenoptera require carbohydrate to sustain flight and oogenesis, and nectar availability is a primary determinant of realised fecundity in the field (Colazza et al., 2023). Experimental provision of flowering resources extends parasitoid lifespan several-fold and raises the number of hosts attacked per female (Herz et al., 2021). Sesame is particularly well suited to this role: its flowers secrete accessible nectar over an extended period, and floral visitation studies document a broad visitor spectrum including small Hymenoptera (Layek et al., 2024). Sesame also retains predatory mirids in other cropping systems by functioning as a banker plant (Castillo et al., 2022),

which may explain why *Paederus fuscipes* and additional coccinellid species appeared only in the sown-refugia treatment here. The attractiveness of a floral patch is mediated by volatile chemistry, and nectar-dwelling microorganisms can modify those volatiles enough to change parasitoid orientation (Cusumano et al., 2023), so the identity of the bund species matters as much as the presence of flowers.

Within the parasitoid guild, egg parasitoids dominated the response. *Trichogramma* sp. doubled from five individuals under cleared and spontaneous bunds to ten under sown refugia, and *Telenomus* species collectively rose from six to nine. Egg parasitoids are among the most carbohydrate-limited natural enemies in rice because of their very short adult lifespan, and their performance in the field is strongly conditioned by rearing history and by the availability of supplementary food (Basana Gowda et al., 2021). Host location in these wasps is mediated by oviposition-induced plant volatiles, and females discriminate host egg age from a distance with considerable precision (Tian et al., 2025). Augmentative release programmes have long been constrained by poor post-release survival; integrating releases with conservation measures of the kind tested here addresses that constraint directly (Babendreier et al., 2022). Honeydew produced by planthoppers also functions as a sugar source for scelionid and mymarid wasps, and its chemical composition varies with host plant genotype and nitrogen status, modulating parasitism independently of floral subsidy (Peñalver-Cruz & Horgan, 2022).

Detritivore abundance increased alongside parasitoids, from 14 individuals under cleared bunds to 20 under sown refugia. Chironomid larvae and phorid flies occupy the aquatic and semi-aquatic compartment of the paddy food web, decomposing organic matter and functioning as alternative prey for generalist predators during the period before herbivores become numerous. Their enrichment under vegetated bunds plausibly reflects greater organic input from litter and root exudates at the field margin. Because generalist predators that feed on detritivores early in the season are already established when herbivores arrive, this compartment contributes indirectly to pest regulation. The decline in predator relative abundance under refugia, from 57.14% to 37.33%, is better read as a consequence of herbivore scarcity than as a cost of the treatment. *Cyrtorhinus lividipennis* accounted for most of that difference, falling from 25 to 5 individuals. This mirid is a specialised consumer of planthopper and leafhopper eggs, and its density tracks the availability of those eggs closely; its predatory capacity and reproductive output are tightly coupled to prey supply (Zhong et al., 2023). Where fewer *Nilaparvata lugens* and *Cicadulina bipunctata* were present, fewer mirids accumulated. Spider abundance, by contrast, remained stable or increased, which fits the generalist foraging strategy of Araneae and their known dependence on structural refuge rather than on any single prey type (Sun et al., 2025). Overwintering studies make the same point at the seasonal scale, with semi-natural

habitat composition governing spider assemblage structure while planting pattern governs ground beetles (Chong et al., 2023).

Temporal variation outweighed every treatment effect. Sampling occasion was significant for all three indices whereas bund vegetation was significant for none, and the quadratic models placed the diversity maximum near 39 DAT in all treatments, coinciding with maximum tillering. Arthropods disappeared entirely from samples after 56 DAT, during grain filling and ripening, when canopy senescence and field drainage remove both habitat and prey. The curvature was best defined under sown refugia ($R^2 = 0.750$, $p = 0.0156$) and weakest under cleared bunds ($R^2 = 0.579$, $p = 0.0746$), indicating that refugia produced a more orderly seasonal trajectory rather than a higher overall level. This phenological dominance over treatment effects has been reported repeatedly in rice, and it implies that habitat management should be evaluated against crop stage rather than against season-long averages (Horgan et al., 2022).

The strong negative correlation between H' and C ($r = -0.811$) is algebraically expected, but its magnitude shows that dips in diversity on particular dates came from numerical dominance by single taxa rather than from taxon loss. Only two assemblages exceeded the 0.5 dominance threshold, 0.89 in T_0 at S_5 and 0.66 in T_1 at S_4 , and neither carried sown refugia. Mean evenness below 0.20 in every treatment describes a community numerically skewed by a few mobile generalists yet monopolised by none of them.

Three limitations bear directly on how the treatment contrasts should be read. The diversity indices were computed from catch pooled across replicate plots, so the analysis of variance partitions variability descriptively and cannot support inference; the absence of a significant bund effect is not evidence that no effect exists. With 232 individuals, three replicates and partial η^2 between 0.09 and 0.20 for bund vegetation, the design had little power to resolve differences of the size observed, and the overlapping confidence intervals in Table 8 express that uncertainty directly. Rarefaction and Chao1 indicate that a quarter to a third of the taxa present escaped detection in every treatment (Table 6; Supplementary Figure S1), so richness contrasts rest on an incompletely censused assemblage, although the rank order survives standardisation to 73 individuals. Finally, canopy and bund catches were pooled per plot, so arthropods on the bund vegetation itself contribute to each treatment total; part of the apparent guild shift may reflect the refugia fauna rather than redistribution within the crop, and stratum-resolved sampling is needed to separate the two.

Neither pest injury nor grain yield was recorded. The experiment was designed to characterise the arthropod assemblage rather than to quantify crop response, and no damage or yield data are held in reserve from this trial. Because the practical case for bund refugia rests on whether the guild shift lowers injury and protects yield, that case cannot be settled from community data alone.

Broader syntheses caution that the benefits of agricultural diversification depend on how a practice is implemented (Seimandi-Corda et al., 2026) and that landscape context can amplify or mask local effects (Ali et al., 2023; Klinnert et al., 2024). Host-plant traits intervene earlier still, since resistance genes, silicon nutrition and volatile emission profiles alter herbivore pressure before natural enemies act (Vu et al., 2022; Khetnon et al., 2022; Yao et al., 2022), and pest- or pathogen-induced shifts in volatile blends reshape parasitoid recruitment in ways bund vegetation cannot control (Sun et al., 2021; Liu et al., 2021). Insecticide use would overturn much of what was observed here (Ray et al., 2023), and competition with pollinators for floral resources, undetected in temperate systems (Alford et al., 2024), warrants testing in tropical paddies. Trait-based selection of bund species, guided by analytical work on nectar and pollen feeding (Gurr et al., 2024) and by evidence that floral provisioning improves coccinellid performance (Hyder et al., 2023), together with attention to abiotic modifiers such as salinity (Ali et al., 2021), offers the clearest route to refining bund composition.

CONCLUSIONS

Maintaining vegetation on rice bunds shifted the arthropod community toward biological control without changing the aggregate diversity statistics. Across nine weekly samplings, 232 individuals in 27 taxa, 20 families and 7 orders were recorded. Sowing sesame and mungbean on the bunds lowered herbivore relative abundance from 11.90% to 5.33%, raised parasitoid relative abundance from 14.29% to 30.67%, and more than doubled the natural-enemy-to-herbivore ratio from 6.00 to 12.75. Spontaneous bund vegetation gave an intermediate response at no establishment cost. A descriptive partition attributed most variation in Shannon diversity, evenness and dominance to sampling occasion rather than to bund treatment, with overlapping treatment confidence intervals; the diversity data neither confirm nor exclude an effect, so the guild composition data carry the argument. Quadratic models placed the diversity maximum near 39 days after transplanting in every treatment, evenness stayed low, no taxon dominated, and rarefaction captured about 68 to 75% of estimated richness. A composite decision-support heuristic combining seven community criteria ranked bunds sown with sesame and mungbean first, at 100.0 against 49.9 for spontaneous vegetation and 2.3 for cleared bunds; the ranking orders the options and does not measure the size of the difference between them. Pest injury and grain yield were not measured here. A replicated multi-season trial recording damage and yield alongside stratum-resolved sampling, with diversity indices computed per plot so the analysis becomes inferential, is the necessary next step before bund refugia can be recommended on economic grounds. Screening candidate bund species against parasitoid longevity and attraction would allow refugia mixtures to be designed for target parasitoid complexes rather than assembled by convenience.

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