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COMMUNITY ECOLOGY AND DAMAGE CHARACTERISTICS OF WOOD-BORING BOSTRICHID BEETLES IN STORED TIMBER

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ABSTRACT
Background: Bostrychid beetles (Coleoptera: Bostrichidae) have a worldwide distribution but are predominantly found in tropical and arid regions. One of the most characteristic signs of infestation is the perfectly circular exit holes created by adults at emergence, with diameters varying by species. The boring activity of larvae causes damage in stems, branches, and twigs of dead, damaged, or stressed hosts, and tunnelling through host tissues leads to extensive frass-filled galleries. An experiment was conducted to document the population dynamics of wood-boring bostrychid beetles collected from different wood yards at Mettupalayam, Tamil Nadu, India.
Objective: To document the population dynamics, species diversity, and damage assessment of wood-boring bostrychid beetles in commercial wood depots
Methods: Five commercial timber depots located in different areas of Mettupalayam were purposively selected as study sites. Five commercially important wood species, known locally to be susceptible to wood borer attack and widely stocked across the selected depots, were chosen. At each timber depot, infested billets or planks of the five target wood species were visually identified. From each site, multiple infested pieces per wood species were randomly selected from different positions within the stacks (top, middle and bottom layers; inner versus outer stacks) to minimize location bias within depots.
Results: A total of 455 adult beetles belonging to four genera and two families (Bostrichidae and Scolytinae) were recovered from the emergence containers. Of the 455 beetles recovered, 319 individuals (70.11%) were identified as wood-boring beetles of the family Bostrichidae, comprising species of Sinoxylon, Lyctus, and Dinoderus (Table 1). The remaining beetles included Scolytus sp. (6 individuals) and unidentified beetles that did not belong to Bostrichidae. Within the total assemblage, four genera of wood-boring beetles were identified. Wood-boring beetles recovered from wood depots between September 2019 and February 2020. Analysis of exit hole diameters across all five wood species revealed a highly consistent pattern: the 1.1–2.0 mm size class contained the greatest number of exit holes in every wood species, followed by the ≤ 1.0 mm class. The highest beetle emergence was recorded during weeks 8 and 10 of the observation period. Maximum emergence of 6 individuals recorded in week 10, recovered specifically from bamboo substrates.
Conclusion: It was demonstrated that wood-boring beetle assemblages in commercial timber depots at Mettupalayam are overwhelmingly dominated by the family Bostrichidae, which contributed 65.00–74.66% of all beetles recovered across the five study sites. The consistently high proportional representation of Bostrichidae across all five depots in the present study regardless of differences in depot size, stacking methods, or timber volume. The dominance of the 1.1–2.0 mm exit hole size class across all five wood species, followed by the ≤ 1.0 mm class, has important diagnostic significance. Although the overall beetle fauna was broadly similar across the five depots, significant differences in exit hole density among sites were observed for some wood species, particularly silver oak and eucalyptus. This spatial variation suggests that local depot conditions modulate infestation intensity even when the underlying pest species pool is similar.

KEYWORDS: Bostrichidae; Sinoxylon; wood-boring beetles; timber depot; species diversity; exit holes; Mettupalayam

INTRODUCTION
Bostrychid beetles (Coleoptera: Bostrichidae) have a worldwide distribution but are predominantly found in tropical and arid regions, with new geographical records continuing to be added globally (Liu, 2010). These beetles pose a significant

economic threat to the forestry and timber industries, particularly in tropical countries, where their larvae and adults reduce wood to powdery frass (Liu et al., 2008; Beaver et al., 2011). One of the most characteristic signs of infestation is the perfectly circular exit holes created by adults at emergence, with diameters varying by species (Herald et al., 2009). The boring activity of larvae causes damage in stems, branches, and twigs of dead, damaged, or stressed hosts, and tunnelling through host tissues leads to extensive frass-filled galleries (El Obied, 1998; Halperin and Geis, 1999; Liu et al., 2008; Beaver et al., 2011).
Wood-damaging Bostrichidae of the genus Sinoxylon are commonly found in tropical areas, especially in arid regions, where they damage a wide range of soft and hardwoods (Bushara, 1981). Sinoxylon anale Lesne is one of the principal timber pests in India, recorded as a major wood borer in poles and logs across several states including Kerala and Maharashtra (Mathew, 1982; Savoldelli and Regalin, 2009). Sinoxylon conigerum Gerstäcker has been reported to attack pigeon pea (Cajanus cajan), mango (Mangifera indica), cassava (Manihot esculenta), cotton (Gossypium hirsutum), and guava (Psidium guajava) (Balasubramanya et al., 1990; Tomimura, 1993). In southern Thailand, Sinoxylon anale and Sinoxylon unidentatum are the most destructive beetles of rubber-sawn wood (Halperin and Geis, 1999; Liu et al., 2008).
The genus Dinoderus, comprising bamboo powderpost beetles, includes several major pests of bamboo and stored wood products, with species such as D. minutus, D. japonicus, and D. brevis attacking harvested culms and finished products worldwide. The family Bostrichidae also includes Lyctus spp. (true powderpost beetles), which preferentially attack sapwood of hardwoods and are of significant quarantine concern in international timber trade.
Despite the economic importance of stored timber pests, comprehensive studies on species composition, diversity, and damage characterization of wood-boring bostrychid beetles in timber depots of southern India remain scarce. The present study was undertaken to document the population dynamics, species diversity, and damage assessment of wood-boring bostrychid beetles in commercial wood depots at Mettupalayam, Tamil Nadu, India.

MATERIALS AND METHODS

Description of the Study Area

The present investigation was conducted in and around Mettupalayam (11.30° N, 76.95° E; elevation 314 m above mean sea level), a major timber processing hub located in Coimbatore district, Tamil Nadu, India. Mettupalayam is situated at the foothills of the Nilgiri hills in the Western Ghats biodiversity hotspot, on the banks of the Bhavani River, a major tributary of the Cauvery. The study area experiences a tropical savanna climate characterized by three distinct seasons: hot summers (March–May, 25–38 °C), the southwest monsoon period (June–September, with moderate to heavy rainfall), and mild winters (November–February, 15–25 °C). Mean annual rainfall is approximately 800–1000 mm, received primarily during the southwest monsoon, with supplemental northeast monsoon showers during October–November. These warm, humid climatic conditions are particularly conducive to the development, reproduction, and emergence of wood-boring beetles of the family Bostrichidae and related taxa.
Mettupalayam serves as a key transit point for timber harvested from the surrounding Nilgiri hills, the Western Ghats forests, and plantation areas. The town houses numerous commercial wood depots and sawmills that receive, process, and store a wide range of hardwood and softwood species, making it an ideal location for studying the diversity and damage patterns of stored timber pests.

Selection of Timber Depots

Five commercial timber depots located in different areas of Mettupalayam were purposively selected as study sites based on the following criteria: (i) the volume and diversity of timber species handled, (ii) the presence of visible signs of wood-boring beetle infestation (exit holes, frass accumulation), and (iii) the willingness of depot owners to participate in the study.

Site No.	Depot Name	Location
1	M/s Sajeena Timber	Kothagiri Road, Mettupalayam
2	M/s Sudharsan Timber	Annur Road, Mettupalayam
3	M/s Gayathri Timber	Odanthurai, Mettupalayam
4	M/s Alim Timbers	Ooty Road, Mettupalayam
5	M/s Vijay Sawmill	Kothagiri Road, Mettupalayam

Each depot was treated as an independent study site for all quantitative analyses of beetle abundance, exit hole density, and damage assessment.

Selection of Wood Species

Five commercially important wood species, known locally to be susceptible to wood borer attack and widely stocked across the selected depots, were chosen for detailed sampling:

- Silver oak (Grevillea robusta A. Cunn. ex R. Br., Proteaceae) — a fast-growing plantation species widely used in furniture, plywood, and tea/coffee shade plantations in southern India.
- Teak (Tectona grandis L.f., Lamiaceae) — one of the most valued timber species globally, known for its natural durability and resistance to biological degradation.
- Neem (Azadirachta indica A. Juss., Meliaceae) — a multipurpose tree with well-documented insecticidal properties, widely used for furniture and agricultural impl
- Eucalyptus (Eucalyptus spp., Myrtaceae) — widely planted in southern India for pulpwood, poles, and construction timber.

- Rosewood (Dalbergia latifolia Roxb., Fabaceae) — a premium hardwood known for its dense heartwood and high natural durability.

These species represent a gradient of wood density, heartwood extractive content, and natural durability, thereby allowing comparative assessment of beetle susceptibility.

Sample Collection Protocol

Identification of infested material

At each timber depot, infested billets or planks of the five target wood species were visually identified based on the following diagnostic criteria:

- Presence of circular to oval exit holes on bark or sawn surfaces
- Accumulation of fine, powdery frass (boring dust) on or beneath the timber stacks
- Discoloration, softening, or structural weakening of the sapwood
- Evidence of adult beetle activity (live or dead adults in the vicinity of stacks)

Sampling Period and Frequency

Infested wood samples were collected between September 2019 and February 2020, a six-month period that encompassed the late southwest monsoon, northeast monsoon, and winter seasons. Following collection, beetle emergence from the billets was monitored over a continuous 31-week observation period in the laboratory. Observations were made at least twice per week to capture successive cohorts of emerging adults from the same billets, enabling the quantification of temporal abundance trends for different beetle genera throughout the emergence period.

Laboratory Maintenance and Beetle Emergence Protocol

Incubation conditions

Labeled billets were transported immediately after collection to the Entomology/Wood Protection Laboratory. Individual billets from each wood species × site combination were placed in separate clear plastic emergence containers (transparent polypropylene boxes) to avoid cross-contamination between treatments.

Containers were maintained under controlled ambient conditions of approximately 26 ± 1 °C and 60 ± 10% relative humidity (RH), following the methodology of Sittichaya and Beaver (2009) for rearing tropical wood-boring Bostrichidae. Containers were lightly covered with fine mesh or perforated lids to:Allow adequate air exchange and prevent moisture build up, Prevent escape of emergent beetles, and facilitate visual detection of positively phototropic adults that migrate towards lighted surfaces upon emergence.

Collection of emerging beetles

At each observation interval (twice weekly), emerging adult beetles were carefully collected from the containers using soft camel-hair brushes and fine entomological forceps to avoid damage to delicate taxonomic structures (antennae, tarsi, elytral sculpture). Adults were immediately transferred into labeled glass vials containing ethyl acetate for euthanization and short-term preservation.

Morphological Identification of Beetles

Sorting and preparation

All adult beetles recovered from the emergence containers were initially sorted to family level under a binocular stereomicroscope (10–40×) using external morphological characters.

Genus-level identification

Within the family Bostrichidae, beetles were further identified to genus level using diagnostic characters specific to tropical Bostrichidae:

- Sinoxylon spp.: Body cylindrical, 3–6 mm; reddish-brown to dark brown; pronotum strongly convex with conspicuous anterior rasps or denticles; elytra truncate posteriorly, often with marginal teeth on the declivity; antennae 10-segmented with a 3-segmented club.
- Lyctus spp. (Lyctinae): Body narrow, elongate, flattened; 2–7 mm; reddish-brown; head visible from above (not concealed by pronotum); antennae with a 2-segmented club; exit holes typically 0.8–1.6 mm diameter.
- Dinoderus spp.: Body small, cylindrical, 2–4 mm; dark brown to black; pronotum with prominent anterior rasps; elytra without conspicuous declivity teeth; often associated with bamboo substrates.
- Scolytus spp. (Curculionidae: Scolytinae): Small bark beetles, 2–5 mm; body compact, cylindrical; head prominent; elytra covering entire abdomen; typically associated with bark and phloem tissues.

Identifications were confirmed using standard taxonomic keys for Indian Bostrichidae (Beeson and Bhatia, 1937; Mathew, 1982) and supplemented with reference to published descriptions and illustrations (Liu, 2010; Liu et al., 2021; Beaver et al., 2011).

RESULTS

Beetle Assemblage Composition and Bostrichidae Dominance

Overall beetle recovery

A total of 455 adult beetles belonging to four genera and two families (Bostrichidae and Scolytinae) were recovered from the emergence containers during the 31-week observation period from billets of five wood species collected across five commercial timber depots at Mettupalayam. This represents the cumulative emergence from samples collected between September 2019 and February 2020, with monitoring extending until beetle emergence ceased.

Dominance of Bostrichidae

Of the 455 beetles recovered, 319 individuals (70.11%) were identified as wood-boring beetles of the family Bostrichidae, comprising species of Sinoxylon, Lyctus, and Dinoderus (Table 1). The remaining beetles included Scolytus sp. (6 individuals) and unidentified beetles that did not belong to Bostrichidae. The family Bostrichidae consistently dominated the beetle assemblage across all five study sites, with proportional contributions ranging from 65.00% to 74.66% of total beetles collected at each site (Table 1 and Fig 1):

Fig. 1. Species composition of wood boring beetles (N = 455). Sinoxylon sp. dominated with 76.70 % relative abundance

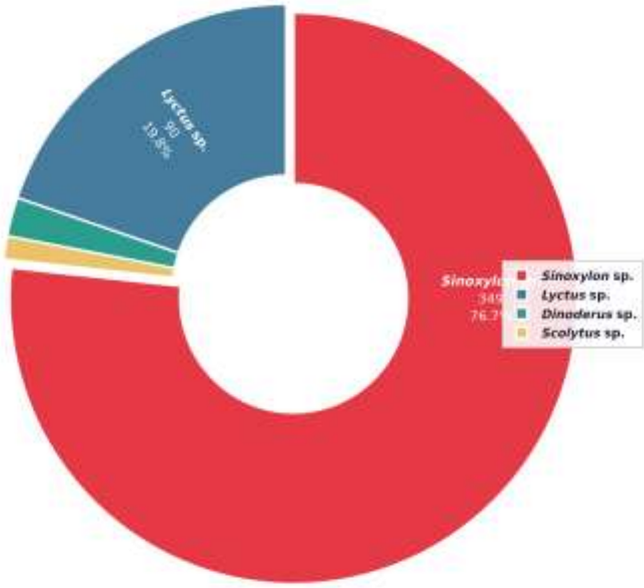

Table 1. Percent contribution of the family Bostrichidae recovered from wood depots at Mettupalayam

Study Site	Total Beetles (N)	Bostrichidae (N)	Contribution (%)
Site 1: M/s Sajeena Timber, Kothagiri Road	120	78	65.00
Site 2: M/s Sudharsan Timber, Annur Road	90	65	72.20
Site 3: M/s Gayathri Timber, Odanthurai	110	78	70.90
Site 4: M/s Alim Timbers, Ooty Road	60	42	70.00
Site 5: M/s Vijay Sawmill, Kothagiri Road	75	56	74.66

The highest number of beetles was collected from Site 1 (120 individuals), while Site 4 yielded the fewest (60 individuals). The highest proportional contribution of Bostrichidae was recorded at Site 5 (74.66%), whereas the lowest was at Site 1 (65.00%), suggesting that Bostrichidae dominance was relatively consistent but independent of total beetle abundance. These results confirm that Bostrichidae constitute the primary wood-boring beetle family infesting stored timber in the Mettupalayam timber trade.

Species Composition and Relative Abundance

Genus-level distribution

Within the total assemblage, four genera of wood-boring beetles were identified (Table 2):

Table 2. Wood-boring beetles recovered from wood depots between September 2019 and February 2020

Insect Species	Family	No. of Beetles	Relative Abundance (%)
Sinoxylon sp.	Bostrichidae	349	76.70
Lyctus sp.	Bostrichidae (Lyctinae)	90	19.78
Dinoderus sp.	Bostrichidae (Dinoderinae)	10	2.19
Scolytus sp.	Curculionidae (Scolytinae)	6	1.31
Total		455	100.00

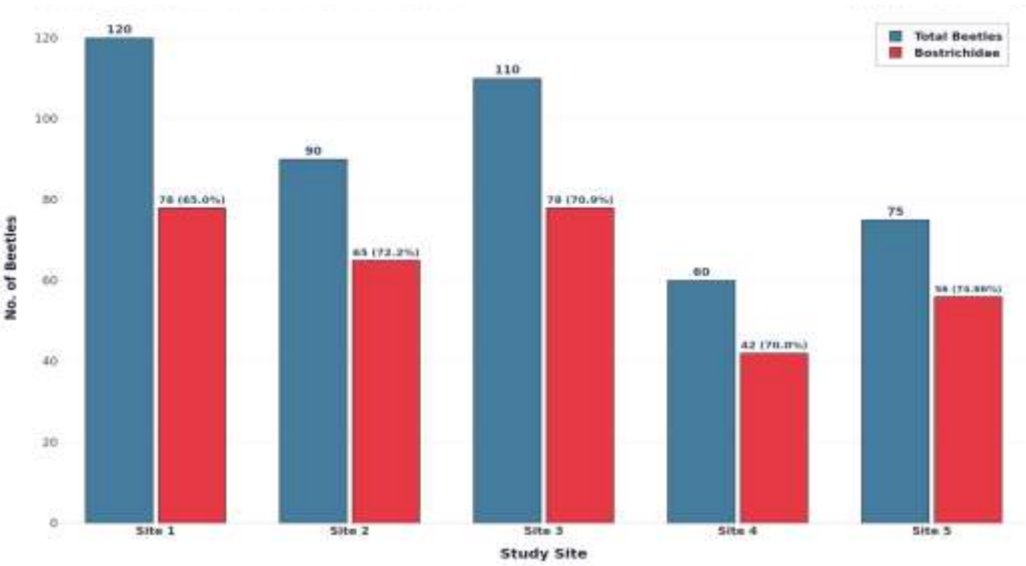

Fig. 2. Percent contribution of Bostrichidae Across Wood Depots Bostrichidae ranged from 65.00 % of total beetles.

Dominance of Sinoxylon sp.

Sinoxylon sp. was overwhelmingly the most abundant taxon, accounting for 349 of the 455 individuals (76.70%). This represented more than three-quarters of the entire beetle assemblage and more than four times the abundance of the next most common genus. This extreme numerical dominance indicates that Sinoxylon is the principal wood-boring beetle genus in stored timber depots in the Mettupalayam region and likely the primary agent responsible for the majority of observed exit holes and wood damage.

Secondary and minor species

Lyctus sp. formed the second most abundant group with 90 individuals (19.78%), representing approximately one-fifth of the total assemblage. As powder post beetles that preferentially attack starchy sapwood of hardwoods, Lyctus species are globally recognized as serious pests of stored and processed timber. Dinoderus sp. was recovered in low numbers 10 individuals (2.19%) primarily from bamboo substrates stored in the depots. Bamboo powderpost beetles of the genus Dinoderus are well-documented pests of harvested bamboo culms and finished bamboo products in tropical Asia. Scolytus sp. was the least abundant taxon, represented by only 6 individuals (1.31%). Bark beetles of the genus Scolytus are typically associated with bark and phloem tissues of living or recently dead trees and their occurrence in stored timber may represent opportunistic colonization of freshly felled logs prior to depot storage.

Temporal Pattern of Beetle Emergence

Continuous emergence of Sinoxylon sp.

Weekly monitoring of the emergence containers over the 31-week study period revealed that Sinoxylon sp. was recorded in every week of observation, confirming its continuous breeding activity and overlapping generations in stored timber under the prevailing laboratory conditions. This is consistent with published reports that Sinoxylon anale can emerge throughout the year without a regular generational sequence, with the life cycle lasting from a minimum of 3 months to over 4 years depending on environmental conditions and wood quality.

Peak emergence periods

The highest beetle emergence was recorded during weeks 8 and 10 of the observation period:

Sinoxylon sp.: 25 adults per week in both week 8 and week 10 — the maximum weekly count recorded for any genus during the study. Lyctus sp.: Maximum emergence of 6 individuals recorded in week 10. Dinoderus sp.: Maximum emergence of 6 individuals recorded in week 10, recovered specifically from bamboo substrates. The convergence of peak emergence for all three Bostrichidae genera in week 10 suggests that the environmental conditions in the laboratory at that time point (approximately 10 weeks post-collection, corresponding to late November 2019) may have been optimal for adult eclosion and emergence, possibly reflecting synchronized development of larvae from the initial colonization event in the field.

Emergence pattern of minor species

Scolytus sp. showed sporadic emergence with only 6 individuals recovered across the entire 31-week period, precluding meaningful temporal analysis for this genus.

Species Diversity of the Beetle Assemblage

Diversity indices

Four community ecology indices were computed from the total beetle assemblage data (N = 455 individuals, S = 4 species) (Table 3):

Table 3. Species diversity indices of wood-boring beetles in timber depots at Mettupalayam

Diversity Index	Value	Interpretation
Shannon–Wiener Index (H')	1.34	Moderate diversity
Margalef Species Richness (R)	0.43	Low species richness
Simpson's Diversity Index (D)	3.67	Moderate to high diversity
Pielou's Evenness Index (J')	0.97	Very high evenness

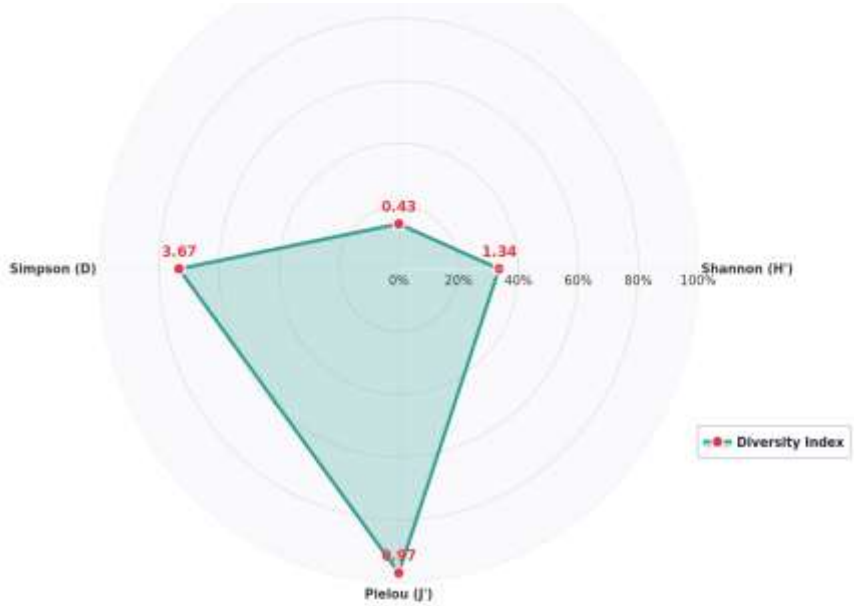

Fig. 3. Species Diversity Profile of Beetle Assemblage

Interpretation of diversity patterns

The Shannon–Wiener Index of H' = 1.34 falls at the lower end of the range typically observed in ecological communities (1.5–3.5), indicating moderate diversity with a strong dominance component. This value reflects the overwhelming numerical predominance of Sinoxylon sp. (76.70%), which reduces the informational uncertainty associated with randomly sampling the assemblage.

The Margalef Species Richness Index of R = 0.43 confirms low taxonomic richness relative to sample size, which is expected given that only four genera were recovered from 455 individuals. In communities with few species but large total abundances, the logarithmic correction in Margalef's formula yields low values.

The Simpson's Diversity Index of D = 3.67 (reciprocal form), approaching the maximum possible value of S = 4 for a four-species community, suggests that despite the abundance skew, the community has moderate to high effective diversity when dominance weighting is applied.

Most notably, Pielou's Evenness of J' = 0.97 is remarkably high, approaching the theoretical maximum of 1.0. This seemingly paradoxical result high evenness in a numerically dominated community is a well-documented mathematical artefact that arises because the Shannon index (from which J' is derived) uses logarithmic weighting that compresses the scale of extreme dominance, particularly when S is small. With only four species, even moderate differences in abundance can yield high calculated evenness. This result should therefore be interpreted cautiously and in conjunction with the other indices.

Exit Hole Density on Different Wood Species

Overview of infestation intensity

The mean number of exit holes per billet varied significantly ($P \leq 0.05$) among sites within each of the five wood species, as well as dramatically between wood species (Table 4). The five wood species could be ranked in decreasing order of susceptibility based on exit hole density as follows:

Silver oak >> Eucalyptus > Neem >> Teak ≈ Rosewood

Table 4. Mean number of exit holes (± SE) of wood-boring beetles on different woods across five study sites

Wood Species	Site 1	Site 2	Site 3	Site 4	Site 5
Silver oak	27.76 ± 3.53^{a} (N=14)	28.58 ± 1.31^{a} (N=12)	31.20 ± 1.81^{b} (N=14)	32.00 ± 2.31^{b} (N=12)	32.10 ± 2.24^{b} (N=12)
Teak	3.86 ± 2.09^{e} (N=15)	2.85 ± 1.79^{c} (N=14)	1.66 ± 1.07^{b} (N=12)	3.15 ± 1.90^{d} (N=13)	1.21 ± 1.12^{a} (N=12)

Neem	19.09 ± 2.07^{c} (N=11)	19.61 ± 2.14^{ab} (N=13)	20.08 ± 1.62^{bc} (N=12)	19.62 ± 1.82^{a} (N=16)	20.50 ± 1.50^{b} (N=14)
Eucalyptus	24.58 ± 1.44^{d} (N=12)	23.46 ± 2.22^{c} (N=13)	24.85 ± 1.95^{e} (N=14)	22.91 ± 2.10^{b} (N=12)	22.50 ± 2.15^{a} (N=12)
Rosewood	3.15 ± 1.46^{ab} (N=13)	3.21 ± 1.80^{a} (N=14)	2.66 ± 1.54^{d} (N=15)	2.93 ± 2.20^{b} (N=16)	2.83 ± 1.94^{c} (N=12)

Means followed by the same superscript letter within a row are not significantly different at P ≤ 0.05 (Student–Newman–Keuls Test)

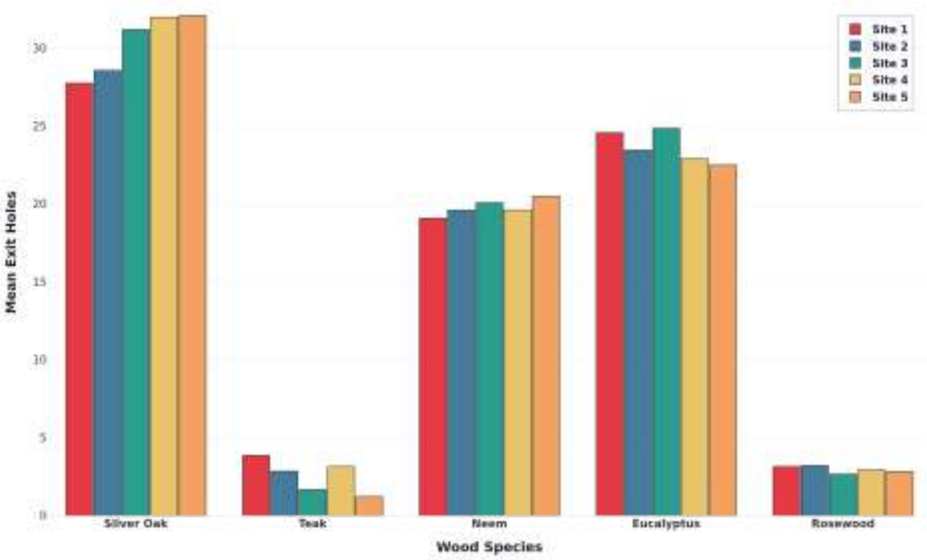

Fig. 4. Mean Exit Hole Density Across Wood Species and Sites

Silver oak (Grevillea robusta)
Silver oak exhibited the highest overall infestation levels among all wood species studied. Mean exit hole counts ranged from 27.76 ± 3.53 (Site 1) to 32.10 ± 2.24 (Site 5) per billet. SNK test results revealed that billets from Sites 3, 4, and 5 had significantly higher numbers of exit holes (bearing the superscript "b") compared to those from Sites 1 and 2 (superscript "a"). The mean numbers of exit holes at Sites 3 (31.20), 4 (32.00), and 5 (32.10) were statistically comparable, forming a homogeneous group. Similarly, Sites 1 and 2 formed a separate, lower group. This pattern suggests spatially variable infestation pressure across depots, possibly related to differences in storage duration, timber age, moisture content, or proximity to source forests.

Eucalyptus (Eucalyptus spp.)
Eucalyptus showed the second highest infestation with mean exit hole counts between 22.50 ± 2.15 (Site 5) and 24.85 ± 1.95 (Site 3). Significant differences were detected among all five sites (each assigned different superscript letters), with Site 3 recording the highest and Site 5 the lowest exit hole density. The consistently high infestation across sites reflects the vulnerability of eucalyptus sapwood, which is starch-rich and relatively low in natural extractive-based resistance.

Neem (Azadirachta indica)
Neem exhibited moderate infestation levels, with mean exit holes ranging from 19.09 ± 2.07 (Site 1) to 20.50 ± 1.50 (Site 5). The relatively narrow range of values across sites and the overlapping superscript groupings (a, ab, bc) suggest that neem infestation was relatively uniform across depots. Despite the known presence of azadirachtin and other insecticidal compounds in neem bark and wood, the moderate infestation levels observed suggest that these compounds may not provide sufficient protection in stored, seasoned timber where volatile compound concentrations may have diminished.

Teak (Tectona grandis)
Teak demonstrated markedly lower infestation compared to silver oak, eucalyptus, and neem, with mean exit holes ranging from only 1.21 ± 1.12 (Site 5) to 3.86 ± 2.09 (Site 1). Significant inter-site variation was observed (five different superscript groupings), but all values were well below 5 exit holes per billet, confirming the well-documented natural durability of teak timber. Teak heartwood is rich in tectoquinone, dehydrotectol, and other extractives that are toxic or deterrent to wood-boring insects.

Rosewood (Dalbergia latifolia)
Rosewood recorded the lowest overall infestation, with mean exit holes ranging from 2.66 ± 1.54 (Site 3) to 3.21 ± 1.80 (Site 2). These values were comparable to those of teak, confirming that rosewood possesses high natural resistance to bostrychid beetle attack. This resistance is attributed to the dense heartwood structure and high concentrations of phenolic extractives (dalbergiones) characteristic of Dalbergia species. The narrow range of values (2.66–3.21) across sites further suggests that rosewood resistance is consistent regardless of depot conditions.

Exit Hole Size Distribution

Overall pattern

Analysis of exit hole diameters across all five wood species revealed a highly consistent pattern: the 1.1–2.0 mm size class contained the greatest number of exit holes in every wood species, followed by the ≤ 1.0 mm class (Table 5). Exit holes in the larger diameter classes (2.1–3.0 mm, 3.1–4.0 mm, and > 4.0 mm) were progressively rarer. ANOVA detected significant differences ($P \leq 0.05$) in mean exit hole number among size classes for all five wood species.

Table 5. Mean (± SE) number of exit holes per billet by size class on different wood species

Exit Hole Size (mm)	Silver Oak	Teak	Neem	Eucalyptus	Rosewood
≤ 1.0	16.4 ± 3.68^{b}	0.3 ± 0.67^{b}	7.6 ± 2.50^{b}	3.33 ± 1.73^{b}	0.44 ± 0.72^{c}
1.1 – 2.0	33.6 ± 2.36^{a}	1.4 ± 1.07^{a}	17.4 ± 2.98^{a}	25.11 ± 1.61^{a}	1.33 ± 1.11^{a}
2.1 – 3.0	2.6 ± 1.42^{c}	0.3 ± 0.48^{c}	1.4 ± 1.17^{c}	1.88 ± 1.96^{c}	0.66 ± 0.70^{b}
3.1 – 4.0	1.0 ± 1.24^{d}	0.2 ± 0.42^{d}	0.6 ± 0.69^{d}	0.55 ± 0.72^{d}	0.44 ± 0.72^{c}
> 4.0	0.3 ± 0.67^{e}	0.1 ± 0.31^{e}	0.4 ± 0.51^{e}	0.44 ± 0.72^{e}	0.22 ± 0.44^{d}
CD (0.05)	0.34	0.01	0.17	0.236	0.014
SE.d	0.16	0.006	0.085	0.113	0.007
CV (%)	2.46	2.38	2.46	2.86	1.81

Means ± SE in the same column followed by the same superscript letter do not differ significantly at $P \leq 0.05$ (Student–Newman–Keuls Test)

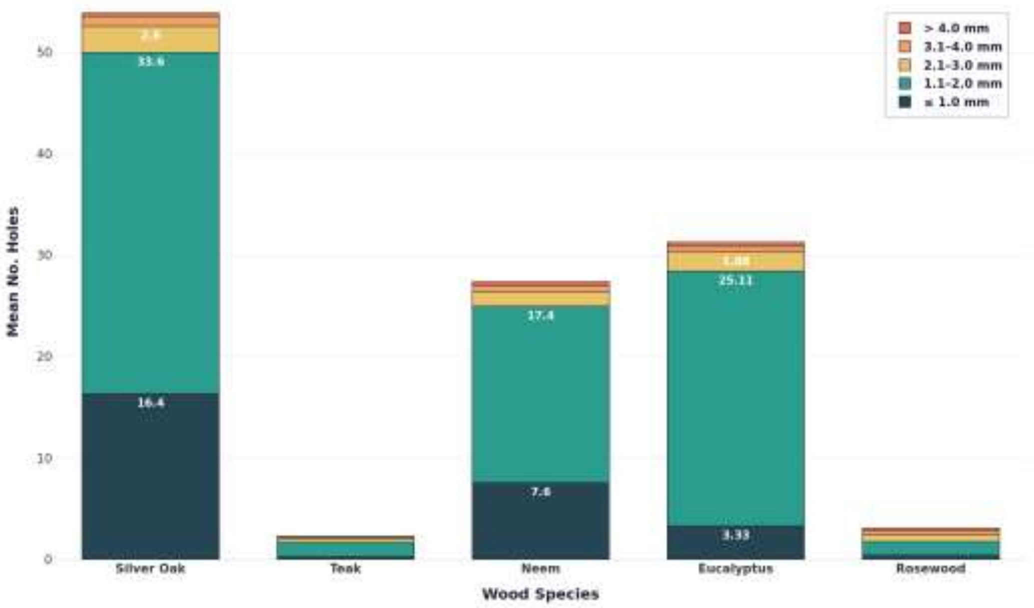

Fig. 5. Exit Hole Size Distribution by Wood Species

Silver oak

In silver oak, which had the greatest absolute number of exit holes, the 1.1–2.0 mm class recorded the highest mean of 33.6 ± 2.36 holes per billet, significantly higher than all other classes. The ≤ 1.0 mm class was second with 16.4 ± 3.68, followed by a steep decline to 2.6 ± 1.42 (2.1–3.0 mm), 1.0 ± 1.24 (3.1–4.0 mm), and 0.3 ± 0.67 (> 4.0 mm). All five size classes differed significantly from each other (five distinct superscript letters: a, b, c, d, e). The dominance of the 1.1–2.0 mm category is consistent with the adult body size of Sinoxylon spp. (typically 3–6 mm body length, producing exit holes of 1–3 mm diameter) and Lyctus spp. (exit holes 0.8–1.6 mm).

Teak

In teak, overall exit hole numbers were very low across all size classes, but the same hierarchical pattern was maintained. The 1.1–2.0 mm class recorded 1.4 ± 1.07 holes per billet, while the ≤ 1.0 mm class had only 0.3 ± 0.67. Larger size classes were almost negligible: 2.1–3.0 mm (0.3 ± 0.48), 3.1–4.0 mm (0.2 ± 0.42), and > 4.0 mm (0.1 ± 0.31). The extremely low CD value (0.01) and CV (2.38%) reflect the highly consistent (though minimal) infestation pattern in teak.

Neem

In neem, the 1.1–2.0 mm class dominated with 17.4 ± 2.98 holes per billet, followed by the ≤ 1.0 mm class with 7.6 ± 2.50. There was a sharp decline to the larger classes: 2.1–3.0 mm (1.4 ± 1.17), 3.1–4.0 mm (0.6 ± 0.69), and > 4.0 mm

(0.4 ± 0.51). All five classes differed significantly (CD = 0.17). The moderate infestation of neem in the 1.1–2.0 mm class is consistent with activity primarily by Sinoxylon sp., the dominant beetle in the assemblage.

Eucalyptus

Eucalyptus showed the second highest total number of exit holes after silver oak. The 1.1–2.0 mm class was by far the most prevalent with 25.11 ± 1.61 holes per billet, while the ≤ 1.0 mm class had only 3.33 ± 1.73. Larger categories were progressively rarer: 2.1–3.0 mm (1.88 ± 1.96), 3.1–4.0 mm (0.55 ± 0.72), and > 4.0 mm (0.44 ± 0.72). The very high proportion of 1.1–2.0 mm holes in eucalyptus (approximately 81% of total holes) strongly implicates Sinoxylon sp. as the principal damaging agent.

Rosewood

Rosewood, consistent with its low overall infestation, showed small absolute numbers across all size classes. The 1.1–2.0 mm class had the highest mean of 1.33 ± 1.11, followed by 2.1–3.0 mm (0.66 ± 0.70), then ≤ 1.0 mm and 3.1–4.0 mm (both 0.44 ± 0.72), and > 4.0 mm (0.22 ± 0.44). The CV was the lowest among all species (1.81%), indicating highly consistent (minimal) infestation across replicates. Despite low absolute values, the same general pattern of 1.1–2.0 mm dominance held true, confirming the ubiquity of the small-bodied bostrychid guild even in resistant wood species.

Cross-species comparison of exit hole size patterns

Comparing across all five species, the proportion of exit holes in the 1.1–2.0 mm class relative to total holes ranged from approximately 43% in rosewood to 81% in eucalyptus, with silver oak (~62%), neem (~63%), and teak (~61%) falling in between. This consistent dominance of the 1.1–2.0 mm category across all wood types strongly supports the conclusion that Sinoxylon sp. and Lyctus sp. both of which produce exit holes within this diameter range are the primary agents of stored timber damage in the Mettupalayam depots. Exit holes exceeding 4.0 mm were extremely rare (≤ 0.44 holes per billet in all species), suggesting negligible contributions from larger-bodied cerambycids or large bostrichid species to the overall damage complex.

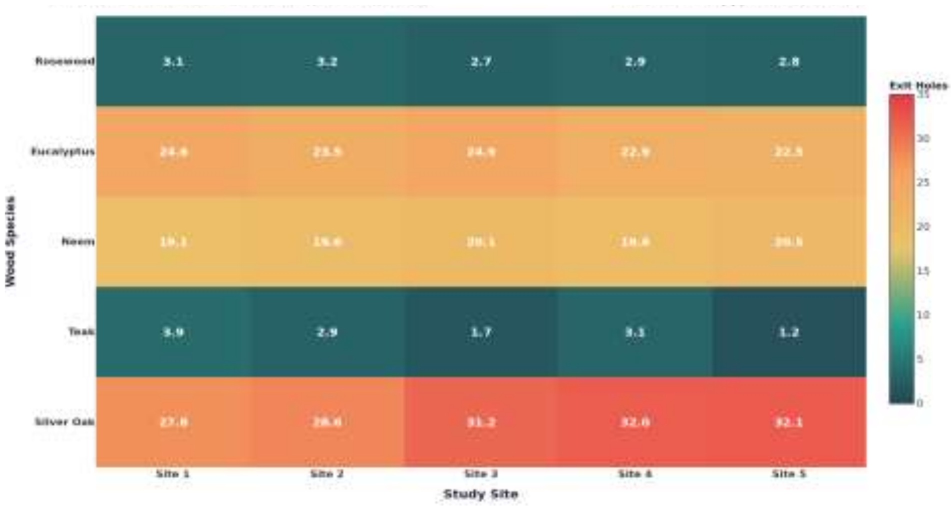

Fig. 6. Heatmap of Exit Hole Intensity (Wood Species x Site)

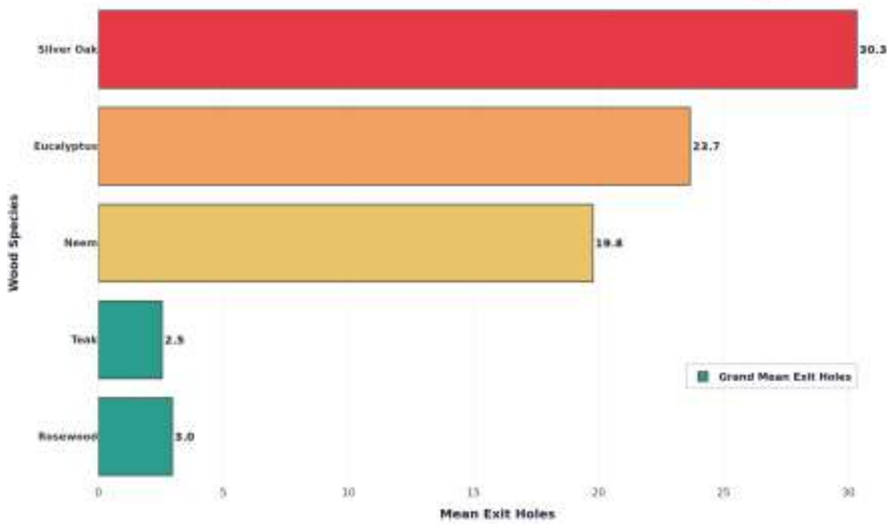

Fig. 7. Wood Species Susceptibility Ranking

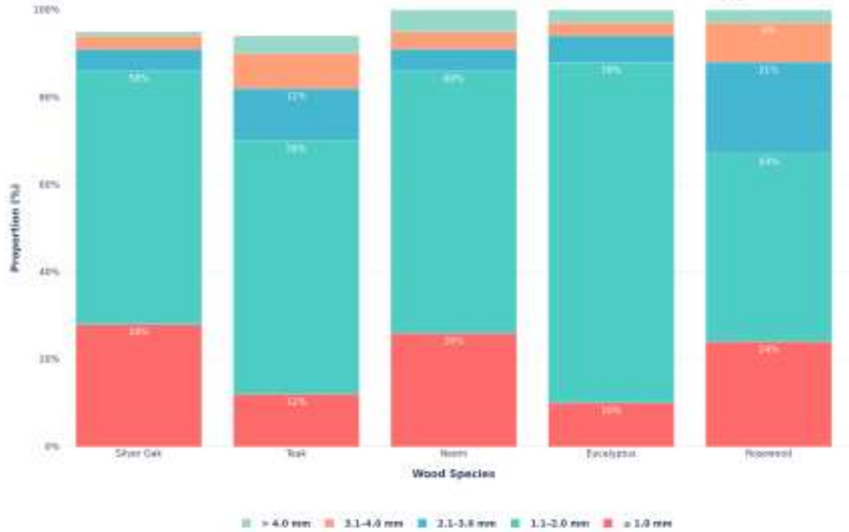

Fig. 8. Wood Species Susceptibility Ranking

DISCUSSION

Dominance of Bostrichidae in Stored Timber Depots

The present study demonstrates that wood-boring beetle assemblages in commercial timber depots at Mettupalayam are overwhelmingly dominated by the family Bostrichidae, which contributed 65.00–74.66% of all beetles recovered across the five study sites. This finding is in strong agreement with earlier surveys of stored timber pests in tropical India. Mathew (1982) documented approximately a dozen species of beetles as pests of stored rubberwood in Kerala, and reported that maximum damage was caused by bostrychids, particularly Sinoxylon anale Lesne and Xylothrips flavipes (Illiger), which attack both round logs and finished products (Mathew, 1982; KFRI Research Report No. 10). A subsequent investigation by the Kerala Forest Research Institute (KFRI Research Report No. 189) confirmed that borers and staining fungi remain the most serious problems for effective utilization of rubberwood timber, with bostrychids consistently constituting the dominant pest guild in timber yards across Kerala (Mathew, 2005). Similarly, Nair (2007), in his comprehensive treatment of tropical forest insect pests, observed that Bostrichidae are the most economically important family of beetles attacking stored timber in tropical countries, and that their damage in timber depots, sawmills and processing facilities can result in significant financial losses to the forestry and timber industries (Nair, 2007).

The consistently high proportional representation of Bostrichidae across all five depots in the present study regardless of differences in depot size, stacking methods, or timber volume suggests that this family is ubiquitously associated with stored timber in the Mettupalayam region and that local environmental conditions (warm tropical climate, moderate to high humidity) strongly favour bostrychid establishment and reproduction. Liu (2010) noted that Bostrichidae have a worldwide distribution but are predominantly found in tropical and arid regions, with new geographical records continuing to be added as international timber trade expands (Liu, 2010).

Sinoxylon sp. as the Principal Stored Timber Pest

Within the beetle assemblage, Sinoxylon sp. was overwhelmingly dominant, accounting for 76.70% of all individuals recovered (349 of 455 beetles). This level of dominance clearly identifies Sinoxylon as the principal wood-boring beetle genus in stored timber depots in the Mettupalayam region. This result is strongly corroborated by multiple independent studies across India. Shukla and Rajak (2007) reported that Sinoxylon anale Lesne is "one of the most destructive wood borers found in India attacking a variety of trees," noting that the beetle bores readily through the bark into the inner sapwood and is a common species in forest timber depots and sawmills (Shukla and Rajak, 2007). In their study on Albizia lebbeck timber, maximum damage by S. anale was recorded on the main trunk, with boring depths reaching 7.5 cm and peak infestation occurring during the monsoon months (Shukla and Rajak, 2007).

Savoldelli and Regalin (2009) documented Sinoxylon anale as a major timber pest associated with wooden pallets in international trade, while Chaudhary et al. (2016) recorded it for the first time as a major wood borer of Xylia xylocarpa (ironwood) poles at a timber depot in Bhandara, Maharashtra, where lowest girth class poles (16–25 cm GBH) exhibited the highest damage of 47.00%, followed by 26–35 cm GBH (22.67%) and 36–45 cm GBH poles (8.67%) (Chaudhary et al., 2016). The European and Mediterranean Plant Protection Organization (EPPO) has classified S. anale as a polyphagous quarantine pest with a very wide host range encompassing at least 60 woody species across multiple families, confirming its status as a major threat to stored timber globally (EPPO Express PRA, 2013; EPPO PRA, 2022).

The continuous emergence of Sinoxylon sp. throughout the 31-week monitoring period in the present study underscores its capacity for overlapping generations and persistent activity in stored timber under tropical depot conditions. The EPPO pest risk analysis for S. anale indicates that the beetle can complete its life cycle within approximately 3–12 months, with considerable variation depending on temperature, wood moisture content, and host species (EPPO Express PRA, 2013). In the laboratory conditions maintained in this study (26 ± 1 °C; 60 ± 10% RH), continuous emergence suggests that multiple cohorts of larvae were present in the billets at the time of collection, and that successive waves of pupation and adult eclosion occurred over the monitoring period.

The peak emergence of Sinoxylon sp. in weeks 8 and 10 (25 adults per week) coincided with peak emergence of Lyctus sp. (6 individuals in week 10) and Dinoderus sp. (6 individuals in week 10), suggesting synchronized developmental responses to the post-collection laboratory environment. Sittichaya and Beaver (2009) observed similar emergence patterns in rubber wood-boring beetles in southern Thailand, where bostrychid emergence peaked 6–12 weeks after sample collection under controlled conditions.

Ecological Significance of Lyctus sp. as a Secondary Pest

Lyctus sp. represented 19.78% of the total assemblage (90 of 455 individuals), confirming the importance of lyctid powderpost beetles as a significant component of the stored timber pest complex in Mettupalayam depots. Lyctus beetles (Bostrichidae: Lyctinae) are globally recognized as serious pests of seasoned hardwood timber, and are second only to termites in their capacity to destroy processed wood products (Bain, 1978; Edde et al., 2005; Jackman, 2006). The larvae of Lyctus brunneus (Stephens), the most common species worldwide, bore exclusively in the sapwood of hardwoods with medium to large vessels and high starch content, reducing the interior to a mass of very fine, talcum powder-like frass (Bain, 1978). The circular emergence holes produced by Lyctus are characteristically small, measuring 0.8–1.6 mm in diameter (Bain, 1978), which is consistent with the predominance of the ≤ 1.0 mm and 1.1–2.0 mm exit hole size classes observed in the present study.

Unlike termites, Lyctus larvae cannot digest cellulose and depend entirely on starch and other nutrients stored in sapwood cells (Goodell et al., 2003). Consequently, heavy Lyctus infestations are typically associated with relatively young timber (less than 10 years old) with high sapwood starch content and moisture contents in the range of 10–20% (Mississippi State University Extension, 2024). The presence of Lyctus sp. in this study is therefore consistent with the stocking of susceptible hardwood timbers, particularly silver oak and eucalyptus, which typically have broad, starch-rich sapwood bands when freshly processed.

Minor Species: Dinoderus sp. and Scolytus sp.

Dinoderus sp. was recovered in low numbers (10 individuals; 2.19%), primarily from bamboo substrates stored alongside timber in some depots. Dinoderus minutus (Fabricius), the bamboo borer, is the best-known species of this genus and is one of the main pests of harvested bamboo in tropical regions, attracted by the high starch content of bamboo culms (Abood and Murphy, 2006; CABI Compendium, 2019). It is native to Asia but has spread widely with the international trade of infested bamboo and bamboo products (CABI Compendium, 2019). Adults are small (2.5–3.5 mm), dark brown, and cylindrical, with the head dorsally concealed by the prothorax (CABI Compendium, 2019). The larval period lasts approximately 61 days, and damage manifests as fine powdery frass filling the galleries of bamboo culms (Jyothna et al., 2015). The modest representation of Dinoderus in this study likely reflects the relatively smaller quantity of bamboo in the sampled depots rather than low pest potential, given that D. minutus can cause near-complete destruction of susceptible bamboo culms under favourable conditions.

Scolytus sp. (Curculionidae: Scolytinae) was the least abundant taxon (6 individuals; 1.31%). Bark beetles of the genus Scolytus are typically associated with bark and phloem tissues of living or recently dead trees and their occurrence in stored timber is generally incidental, representing carry-over from logs that entered the depots shortly after felling (Nair, 2007). Their ecological significance in the stored timber environment is therefore considered negligible.

Species Diversity Indices: Interpretation and Context

The calculated diversity indices (Shannon H' = 1.34, Margalef richness R = 0.43, Simpson's D = 3.67, Pielou's evenness J' = 0.97) characterize a beetle community of low species richness but moderate effective diversity, strongly dominated by a single taxon (Sinoxylon sp.).

The Shannon–Wiener index of H' = 1.34 falls at the lower end of the range typically observed in ecological communities (1.5–3.5 for most biological assemblages), indicating moderate diversity with a strong dominance component (Magurran, 1988; Morris et al., 2014). Shannon H' values for beetle assemblages in natural forest habitats are commonly higher (>2.0), reflecting greater species richness and more equitable abundance distributions in structurally complex environments (Kangkamanee et al., 2011). In contrast, stored timber environments are structurally and micro climatically simpler, favouring a limited subset of species capable of exploiting processed, dry wood under depot conditions (Mathew, 1982; Nair, 2007). The relatively low H' in this study is therefore ecologically expected and consistent with the habitat-filtered nature of timber depot beetle communities.

The Margalef Species Richness Index of R = 0.43 confirms low taxonomic richness relative to sample size, which is a predictable outcome given that only four genera were recovered from a total of 455 individuals. Margalef's index is sensitive to the ratio of species number to total abundance; with large catches dominated by few species, values close to zero are typical (Magurran, 1988).

Pielou's Evenness of J' = 0.97, approaching the maximum of 1.0, appears paradoxical given the strong numerical dominance of Sinoxylon. However, this is a well-documented mathematical artefact that arises when the Shannon index is applied to communities with very low species numbers (S = 4 in this case). Because the Shannon index uses logarithmic weighting, it compresses the scale of extreme dominance, and dividing by ln(S) for a small S yields values close to 1.0 even when one species is overwhelmingly dominant (Morris et al., 2014; Jost, 2006). This result should therefore be interpreted cautiously and in conjunction with the raw abundance data and other indices. The Simpson's Diversity Index of D = 3.67 (reciprocal form), approaching the maximum possible value of S = 4, corroborates that despite the abundance skew, the community has moderate effective diversity when dominance weighting is applied.

Host Wood Susceptibility: The Role of Natural Durability

Marked differences in exit hole density among the five wood species were recorded, with silver oak and eucalyptus exhibiting the highest infestation levels, neem showing moderate susceptibility, and teak and rosewood demonstrating strong apparent resistance. These differences can be attributed primarily to variations in natural durability, wood density, and heartwood extractive chemistry among the species.

Silver oak (Grevillea robusta) — highest susceptibility

Silver oak recorded the highest mean exit hole densities (27.76–32.10 holes per billet across sites), confirming its high susceptibility to bostrychid attack. Grevillea robusta, although widely planted as a shade tree in coffee and tea plantations and used for furniture and plywood in southern India, is well-documented to have low natural durability. Mathew (2005) reported that stored grevillea wood in Kerala is particularly vulnerable to borers and staining fungi, which limits its effective utilization as sawn timber (KFRI Research Report No. 189). The high infestation levels observed in this study are attributable to the relatively low heartwood extractive content, open sapwood structure, and moderate starch content of silver oak, which together create favourable conditions for bostrychid colonization, larval development, and adult emergence.

Eucalyptus (Eucalyptus spp.) — high susceptibility

Eucalyptus exhibited the second highest infestation (mean exit holes 22.50–24.85 per billet), consistent with studies showing that many eucalyptus species are susceptible to insect pests, particularly in their sapwood. Visser et al. (2015) demonstrated that susceptibility of different Eucalyptus species to wood borers varies widely and is related to chemical composition, with susceptible species lacking key defensive metabolites present in more resistant congeners. Constitutive chemical defences in eucalypts, including stilbenes, hydrolysable tannins, and terpenoid volatile compounds, play a key role in modulating beetle and weevil host selection and oviposition (Nascimento et al., 2022). In the context of the present study, the relatively high infestation observed suggests that the eucalyptus assortments stocked in the Mettupalayam depots either belong to more susceptible taxa or that seasoning and storage conditions reduced the efficacy of their natural chemical defences.

Neem (Azadirachta indica) — moderate susceptibility despite biocidal reputation

Neem exhibited moderate infestation levels (19.09–20.50 exit holes per billet). This finding is noteworthy given the widely recognized insecticidal, repellent, and antifeedant properties of neem extracts, particularly azadirachtin (Schmutterer, 1990). However, it is important to distinguish between the bioactivity of fresh neem extracts (which are concentrated in leaves, seeds and bark) and the residual resistance of processed neem timber. Most bioactive secondary metabolites in neem are volatile or semi-volatile and are concentrated in living tissues; their concentrations in seasoned heartwood and sapwood decline substantially with drying, ageing, and processing. Srinivasan et al. (2016) observed that Sinoxylon anale could successfully colonize and develop within allspice (Pimenta dioica) twigs despite the presence of plant secondary metabolites, suggesting that bostrychids can overcome moderate levels of chemical defence in woody hosts. The present data indicate that neem timber should not be assumed to be self-protected against bostrychids, and should be included in routine inspection and protection programmes alongside more susceptible species.

Teak (Tectona grandis) — high natural resistance

Teak exhibited markedly lower infestation (1.21–3.86 exit holes per billet), confirming its well-documented natural durability. The heartwood of teak is extremely resistant to attack by insects and fungi, a property attributed primarily to the presence of tectoquinone (2-methyl anthraquinone) and other quinone derivatives (Rudman et al., 1958; Haupt et al., 2003; Chávez-Salgado et al., 2022). Rudman et al. (1958) first established the relationship between tectoquinone and durability in Tectona grandis, demonstrating its toxicity to subterranean termites and wood-decay fungi (Nature, 181: 721). Subsequent studies confirmed that tectoquinone exhibits strong toxicity and antifeedant activity against Reticulitermes speratus termites, with the compound being far superior to other major heartwood components such as deoxylapachol, tecomaquinone, and squalene (Lukmandaru, 2020). Hassan et al. (2018) further demonstrated that teak heartwood extractives could be transferred to non-durable wood species to improve their resistance against subterranean termites, underscoring the potency of these natural preservatives.

Chávez-Salgado et al. (2022), in their comprehensive review of teak secondary metabolites, confirmed that quinones and anthraquinones in teak heartwood are the primary agents of natural resistance against termites and fungi, and that this resistance varies with tree age, growth rate, and provenance. In the present study, the low but non-zero exit hole densities in teak (up to 3.86 per billet at some sites) likely reflect limited boring activity in sapwood portions of the billets, where extractive concentrations are lower than in heartwood.

Rosewood (Dalbergia latifolia) — highest natural resistance

Rosewood recorded the lowest overall infestation levels (2.66–3.21 exit holes per billet), comparable to teak. Dalbergia latifolia possesses dense heartwood rich in a diverse array of phenolic compounds, including dalbergione, latifolin, and various neoflavonoids, isoflavonoids, and rotenoids (Dwianto et al., 2019; Amamra et al., 2021). GC-MS analyses of D. latifolia heartwood have identified multiple bioactive compounds, including phenanthrene quinones (latinone) and the binary neoflavonoid dalcriodain, which contribute to its anti-termite and antimicrobial properties (Phytojournal, 2021). The high phenolic content and antioxidant activity of rosewood heartwood extractives provide a potent chemical barrier against wood-boring insects, explaining the consistently low exit hole densities observed across all five study sites. These findings confirm that rosewood remains one of the most naturally durable commercial timbers available in southern India.

Exit Hole Size as a Diagnostic Tool for Pest Identification

The dominance of the 1.1–2.0 mm exit hole size class across all five wood species, followed by the ≤ 1.0 mm class, has important diagnostic significance. Jackman (2006) reported that exit hole sizes for Bostrichidae range broadly from approximately 0.8 mm to 9.5 mm depending on species body size. Within this range, Lyctus brunneus produces characteristic small, round exit holes of 0.8–1.6 mm diameter (Bain, 1978), while small to medium Sinoxylon species produce holes of approximately 1–3 mm (Nair, 2007; Jackman, 2006). In contrast, larger bostrichids and cerambycids produce much larger exit holes (>4 mm), often with irregular margins (Jackman, 2006).

The strong predominance of 1.1–2.0 mm holes in the present study accounting for approximately 43% (rosewood) to 81% (eucalyptus) of all exit holes in different wood species is therefore consistent with the emergence data showing that the community is dominated by Sinoxylon sp. and Lyctus sp., both of which produce exit holes within this diameter range. The extreme rarity of exit holes >4.0 mm (≤ 0.44 holes per billet in all species) confirms that larger borers such as cerambycids play a negligible role in the damage complex in these depots. This characteristic size distribution provides a practical, rapid diagnostic tool for field identification: timber lots dominated by small round exit holes (~1–2 mm) in silver oak, eucalyptus, or similar woods can be reliably attributed to bostrychid/lyctid infestation and prioritized for treatment.

Inter-Site Variation and Depot Management Implications

Although the overall beetle fauna was broadly similar across the five depots, significant differences in exit hole density among sites were observed for some wood species, particularly silver oak and eucalyptus. This spatial variation suggests that local depot conditions modulate infestation intensity even when the underlying pest species pool is similar. Factors likely to contribute to inter-site differences include:

- Duration of timber storage: longer storage periods allow more breeding cycles and greater cumulative damage (Mathew, 1982; KFRI Research Report No. 10).
- Stacking density and ventilation: tightly packed stacks with poor air circulation maintain higher humidity in inner surfaces, favouring beetle development (Nair, 2007).
- Timber turnover rate: depots with rapid stock turnover reduce the window for beetle colonization and emergence.
- Proximity to infested source areas: depots near forests or plantations with endemic bostrychid populations may experience higher colonization pressure.

Mathew (1982) reported that S. anale attacked stacks of stored rubberwood most severely where logs were piled for extended periods with poor ventilation and high residual moisture. The present data similarly indicate that sites with consistently higher exit hole counts should be prioritized for sanitation measures (removal of heavily infested stock, cleaning of accumulated frass, improved stacking for ventilation) and preventive chemical treatments (surface application of recommended insecticides or fumigation with phosphine or methyl bromide alternatives).

Potential for Pheromone-Based Monitoring

Recent advances in chemical ecology of Bostrichidae offer promising tools for monitoring and early detection of infestations in timber depots. A comprehensive review by Zhang et al. (2025) documented aggregation pheromones for several bostrichid species, noting that pheromone-based techniques offer environmentally sustainable solutions for integrated pest management (IPM) of stored product and stored timber pests. For the stored grain pest Rhyzopertha dominica (Bostrichidae), aggregation pheromones (dominicalure) have been successfully used for monitoring with Lindgren funnel traps and Japanese beetle traps, with trap catches correlating with infestation levels and enabling timely management decisions (Edde et al., 2005; Wijayaratne et al., 2021). Although species-specific aggregation pheromones have not yet been fully characterized for Sinoxylon anale, the identification and deployment of such pheromones could revolutionize monitoring of bostrychid infestations in Indian timber depots, enabling early detection before economic damage thresholds are reached.

Biological Control Potential

An emerging area of research with relevance to the management of Sinoxylon spp. is the use of entomopathogenic fungi as biocontrol agents. Srinivasan et al. (2016) reported the first natural occurrence of Beauveria bassiana (Bals.-Criv.) Vuill. infecting Sinoxylon anale on allspice (Pimenta dioica) in Kerala, India. Bioassays with the isolated B. bassiana strain demonstrated significant virulence against adult beetles, with LC_{50} values of 3.6×10^6 conidia/mL and ST_{50} values of 6.8 days at 1×10^7 conidia/mL (Srinivasan et al., 2016). This represents a promising avenue for development of mycoinsecticides as part of an integrated management programme for bostrychid beetles in timber depots, particularly where chemical residues on timber are undesirable for downstream applications.

Quarantine and Phytosanitary Significance

The dominance of Sinoxylon sp. in the present study has implications extending well beyond local timber loss. Sinoxylon anale is classified as a quarantine pest in several countries and regions, including Hawaii (USA), Brazil, Argentina, Uruguay, and Paraguay, primarily due to its ability to survive in dry wood and its association with internationally traded timber and wood packaging materials (EPPO Express PRA, 2013; EPPO PRA, 2022). Inadequately treated wooden packaging including pallets, dunnage, and crating has been identified as a major pathway for international spread of bostrychid beetles (Savoldelli and Regalin, 2009; EPPO, 2020). The International Standard for Phytosanitary Measures No. 15 (ISPM 15) mandates heat treatment or methyl bromide fumigation of wood packaging materials to prevent the spread of wood-boring pests in international trade (FAO, 2019).

Given that Mettupalayam is a significant hub for timber flow from the Western Ghats, the high abundance of Sinoxylon in local depots underscores the need for strict adoption of wood protection standards, proper seasoning, and ISPM 15-compliant treatments before timber or packaging materials leave the region, particularly if destined for export markets or for use in packaging of export commodities.

Limitations and Future Research Directions

While the present study provides robust baseline data on composition, diversity, and damage characteristics of wood-boring beetles in Mettupalayam timber depots, several limitations suggest directions for future research:

- Taxonomic resolution: Beetles were identified to genus rather than species level. Integration of detailed morphological identification using taxonomic keys (Beeson and Bhatia, 1937; Liu et al., 2021) with molecular approaches (DNA barcoding of the COI gene region) would enable species-level confirmation (e.g., distinguishing S. anale from other congeners) and more precise risk assessment.
- Life-history parameters under Indian conditions: The present study documented emergence patterns but did not measure developmental rates, fecundity, or survival across different host woods under controlled conditions. Experimental studies of Sinoxylon and Lyctus biology on the five wood species tested, following the rearing protocols of Sittichaya and Beaver (2009), would provide essential parameters for population modelling and prediction of damage trajectories.
- Wood chemistry and susceptibility mechanisms: Comparative analysis of heartwood and sapwood extractive chemistry (total phenolics, specific quinones and flavonoids) across the five wood species, correlated with exit hole densities, would clarify the chemical basis of differential susceptibility. Such work could draw on established methods used for teak (Chávez-Salgado et al., 2022) and rosewood (Dwianto et al., 2019).
- Management efficacy trials: Field trials of integrated management approaches including improved drying and stacking protocols, surface insecticide treatments (bifenthrin, permethrin), fumigation, heat treatment, and biological control with Beauveria bassiana (Srinivasan et al., 2016) need to be conducted and evaluated under operational depot conditions in the Mettupalayam region.
- Pheromone identification: Identification of aggregation pheromones of Sinoxylon anale through headspace volatile collection and GC-MS analysis would be a transformative development, enabling deployment of pheromone-baited traps for monitoring and mass trapping as part of an IPM programme (Zhang et al., 2025).

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