

Diversity and Morphological Variation of Ambrosia Beetles from Forest Plantations in Western Sarawak

by

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Presented to the
FACULTY OF RESOURCE SCIENCE AND TECHNOLOGY
in Fulfillment of the Requirement for the Degree of

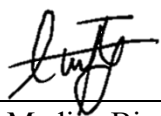
MASTER OF SCIENCE
(Zoology)

2026

UNIVERSITI MALAYSIA SARAWAK

DECLARATION

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ACKNOWLEDGMENT

This research was supported by The Forest Department of Sarawak (FDS) and funded by RMK-12 state fund under Centre of Excellence Project. I would like to thank POLIMA FOREST Bintulu for allowed us to conduct this research in their plantation. We thank the staff of the Forest Health Unit of Industrial Forest Research Centre, FDS for the assistance during data collection, deployment of the traps, and regular monitoring of those traps.

I also thank Jiri Hulcr and other ambrosia beetle expert from the University of Florida, USA for their help to confirm the identification of the beetles in this study.

My sincere gratitude to my supervisor, Dr. Siti Nurlydia Sazali, my co-supervisor, Mdm Wan Nurainie Wan Ismail, and Centre for Graduate Studies, for the advice and support given during my period of study in Universiti Malaysia Sarawak.

Finally, I would like to thank Faculty of Resource Science and Technology, Universiti Malaysia Sarawak, for making it possible for me to complete my study here in Sarawak. Thank you all.

Diversity and Morphological Variation of Ambrosia Beetles from Forest Plantations in Western Sarawak

ABSTRACT

Ambrosia beetles are wood-boring insects (Coleoptera: Curculionidae) that play important ecological roles in ecosystems as pests, particularly in plantation areas. These beetles live in symbiosis with fungi, which can cause plant wilt and even mortality. In Sarawak, ambrosia beetles have been reported to infest exotic tree species such as *Acacia mangium*, *A. crassicarpa*, and *Eucalyptus pellita* in industrial forest plantations. However, despite reports of ambrosia beetle infestations in Sarawak, information on their species diversity and morphological variation remains limited, particularly across different plantation types. Consequently, baseline data linking ambrosia beetle diversity and morphology to monoculture and polyculture forest plantations in Sarawak are still lacking. Hence, this study aimed to investigate the diversity and morphological variation of ambrosia beetles in selected forest plantations in the western Sarawak. Fieldworks were conducted from January to October 2022 at two forest plantations, namely, License Planted Forest 42 (LPF42) in Sampadi, Lundu, and Sabal Forest Reserve (Sabal FR) in Simunjan. Adult ambrosia beetles were sampled using ethanol-baited intercept panel traps. Diversity indices and species assemblages were analysed using PAST software, while morphological variation was assessed through both qualitative and quantitative traits using multivariate ordination and statistical tests. A total of 170 ambrosia beetles were successfully collected, representing 11 species from the subfamily Scolytinae and three species from Platypodinae. LPF42 yielded seven species with 129 individuals, while 11 species comprising 41 individuals were recorded at Sabal FR. The Shannon-Wiener and Simpson's indices were highest in Sabal FR (1.45 and 0.58, respectively), indicating greater species richness and evenness than LPF42 (0.50 and 0.28). *Xylosandrus crassiusculus* was the most dominant species, accounting for 82.94% of total captures. For the morphological assessment, five quantitative and 19 qualitative traits were

analysed to evaluate inter- and intraspecific variation among ambrosia beetles. Quantitative analyses using Principal Component Analysis (PCA), Permutational Multivariate Analysis of Variance (PERMANOVA), Kruskal-Wallis (H), and Similarity Percentage Analysis (SIMPER) revealed that body length and pronotum width were the most important traits separating species, with *Xyleborus ferrugineus* distinguished by its larger body size. Qualitative analyses using Principal Coordinates of Analysis (PCoA), PERMANOVA, SIMPER, Chi-square (χ^2) showed that elytral declivity and pronotal characters provided the strongest diagnostic value, reliably distinguishing species into discrete clusters. *Xylosandrus crassiusculus* exhibited marked morphological conservatism across sites, consistent with its global uniformity. Together, the integration of quantitative and qualitative approaches confirmed species-level boundaries and highlighted contrasting evolutionary strategies within Xyleborini. The findings provide baseline information on ambrosia beetle diversity and morphological variation in Sarawak, addressing a critical gap in regional entomological knowledge. This baseline contributes to future ecological studies and supports forest plantation monitoring and management efforts in Sarawak.

Keywords: abundance, fungus-farming beetle, pest, weevil, *Xylosandrus crassiusculus*

Kepelbagaian dan Variasi Morfologi Kumbang Ambrosia dari Ladang Hutan di kawasan barat Sarawak

ABSTRAK

Kumbang ambrosia merupakan serangga pengorek kayu (Coleoptera: Curculionidae) yang memainkan peranan penting dalam ekosistem hutan, namun turut berpotensi menjadi perosak khususnya dalam persekitaran ladang hutan. Kumbang ini hidup secara simbiosis dengan kulat yang boleh menyebabkan tumbuhan layu dan mati. Di Sarawak, kumbang Ambrosia telah dilaporkan menyerang spesies pokok eksotik seperti Acacia mangium, A. crassicarpa, dan Eucalyptus pellita di ladang hutan. Walau bagaimanapun, meskipun terdapat laporan mengenai serangan kumbang ambrosia di Sarawak, maklumat berkaitan kepelbagaian spesies, serta variasi morfologi masih terhad, khususnya merentas jenis ladang yang berbeza. Sehubungan itu, data asas yang mengaitkan kepelbagaian dan morfologi kumbang ambrosia dengan ladang hutan monokultur dan polikultur di Sarawak masih kurang tersedia. Kajian ini dijalankan untuk menyiasat taburan, menentukan kepelbagaian, dan mengkaji variasi morfologi kumbang ambrosia di beberapa ladang hutan terpilih di wilayah barat Sarawak. Kerja lapangan telah dijalankan dari Januari hingga Oktober 2022 di dua lokasi iaitu Ladang Hutan Berlesen 42 (LPF42) di Sampadi, Lundu, dan Hutan Simpan Sabal (Sabal FR) di Simunjan. Kumbang ambrosia dewasa telah ditangkap menggunakan perangkap panel pintasan yang telah diubahsuai dan menggunakan etanol 70% sebagai umpan. Analisis indeks kepelbagaian dan struktur komuniti spesies dijalankan menggunakan perisian PAST, manakala variasi morfologi dinilai berdasarkan ciri kualitatif dan kuantitatif melalui analisis ordinasi multivariat dan ujian statistik. Sebanyak 170 individu kumbang Ambrosia telah dikutip, mewakili 11 spesies daripada subfamili Scolytinae dan tiga spesies daripada Platypodinae. Di LPF42, tujuh spesies dengan jumlah 129 individu direkodkan, manakala di Hutan Simpan Sabal, 11

spesies dengan 41 individu telah dikutip. Nilai indeks Shannon-Wiener dan Simpson masing-masing adalah tertinggi di Sabal FR (1.45 dan 0.58), menunjukkan kekayaan spesies dan keseimbangan taburan spesies yang lebih tinggi berbanding LPF42 (0.50 dan 0.28). Xylosandrus crassiusculus merupakan spesies yang paling dominan, merangkumi 82.94% daripada jumlah keseluruhan tangkapan. Bagi penilaian morfologi, lima ciri kuantitatif dan 19 cirikualitatif telah dianalisis untuk menilai variasi antara dan dalam spesies kumbang ambrosia. Analisis kuantitatif menggunakan PCA, PERMANOVA, Kruskal-Wallis, dan SIMPER menunjukkan bahawa panjang badan dan lebar pronotum merupakan ciri utama yang membezakan spesies, dengan Xyleborus ferrugineus dikenal pasti melalui saiz badannya yang lebih besar. Analisis kualitatif menggunakan PCoA, PERMANOVA, SIMPER, Chi-square pula menunjukkan bahawa ciri-ciri pada bahagian declivity elytra dan pronotum memberikan nilai diagnostik yang paling kukuh, membezakan spesies secara jelas ke dalam kelompok yang berasingan. Xylosandrus crassiusculus mempamerkan konservatisme morfologi yang ketara di antara tapak kajian, sejajar dengan uniformitinya di peringkat global. Secara keseluruhan, gabungan pendekatan kuantitatif dan kualitatif mengesahkan sempadan spesies serta menonjolkan strategi evolusi yang berbeza dalam kalangan Xyleborini. Hasil kajian ini menyediakan maklumat asas mengenai kepelbagaian kumbang ambrosia dan variasi morfologinya di Sarawak, sekali gus menangani jurang pengetahuan yang kritikal dalam bidang entomologi serantau. Maklumat asas ini menyumbang kepada kajian ekologi pada masa hadapan serta menyokong usaha pemantauan dan pengurusan ladang hutan di Sarawak.

Kata kunci: Kelimpahan, kumbang penanam kulat, serangga perosak, kekabuh, Xylosandrus crassiusculus

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LIST OF ABBREVIATIONS

CGS	Centre for Graduate Studies
UNIMAS	Universiti Malaysia Sarawak
FDS	Forest Department Sarawak
IUFRO	International Union of Forest Research Organizations
FAO	Food and Agriculture Organization
AFC	Ambrosial Fusarium Clade
LPF42	License Planted Forest 42
Sabal FR	Sabal Forest Reserve
MINT PT	Modified Intercept Panel Trap
PCA	Principal Component Analysis
PCoA	Principal Coordinates of Analysis
PERMANOVA	Permutational Multivariate Analysis of Variance
SIMPER	Similarity Percentage
PCoA	Principal Component of Analysis
PAST	Paleontological Statistics

CHAPTER 1: INTRODUCTION

1.1 Background of Study

Sarawak, a Malaysian state located in Borneo, the third largest island in the world (Hon & Shibata, 2013), accommodates a wide range of forest types, including mixed dipterocarp, mangrove, peat swamp, montane, limestone, and heath forests (Hazebroek & Abang Morshidi, 2000). These rich ecosystems are home to over 277 mammalian species, 673 bird species, 400 freshwater fish species, 200 herpetofauna species, and at least 15,000 flowering plant species (Chong et al., 2018). Additionally, Hill & Abang (2005) identified 29 insect orders within Borneo, encompassing at least 51,530 known insect species.

Biodiversity richness is vital for maintaining forest ecosystems, particularly in areas where forests are key to ecological balance and economic value. Forest plantations, whose main objective is often the production of timber or fuel wood (plantations provided about 35% of the global wood supply in 2000) but some are established to reduce erosion, fix carbon, or provide other environmental, economic, or social benefits (Brockerhoff et al., 2008). According to the current Food and Agriculture Organization (FAO) and International Union of Forest Research Organisations (IUFRO), plantation forests are established through planting or seeding of one or more indigenous or introduced tree species in the process of afforestation or reforestation (FAO, 2006). Plantation forests make up only about 3.5% of the global forest area (approximately 140 million hectares), yet their extent is expanding by 2–3 million hectares, or about 2%, annually (Brockerhoff et al., 2008). Studies from various countries highlight that plantation forests can provide essential habitats for a diverse range of native plants, animals, and fungi (Carnus et al., 2006). Even rare and threatened species are increasingly found within plantation landscapes as more focused surveys are conducted. For instance, the critically endangered ground beetle *Holcaspis brevicula*, a species endemic to a specific locality, is believed to rely on plantation forests as its sole remaining habitat (Brockerhoff et al., 2005).

Interest in forest plantations in Sarawak began in the early 1920s with trials of both indigenous and exotic tree species. By 1965, the Reforestation Research Program was established to focus on fast-growing exotic species, particularly conifers. The development of planted forests became a long-term strategy to provide a sustainable and alternative wood supply for Sarawak's wood-based industries, aiming to reduce harvesting pressure on natural forests while enhancing the state's forest cover. Between 1997 and 2013, plantation areas accumulated to 317,447.10 hectares, with species primarily consisting of fast-growing exotics and some indigenous varieties, including *Acacia* spp., *Paraserianthes falcataria* (Batai), *Eucalyptus* spp., and *Neolamarckia cadamba* (Kelampayan) (Forest Department Sarawak, 2020).

Forest plantations in Sarawak also include monoculture plantations, often consisting of a single tree species, and polyculture plantations, which incorporate multiple or more tree species. The study of insect diversity, particularly insect pest species, within these plantation types is crucial for understanding ecosystem health and the potential implications of forest management practices on biodiversity. In line with these aims, the Forest Department Sarawak (FDS) actively monitors and manages forest health to ensure sustainable forestry practices and mitigate pest threats.

Insect pests and diseases are serious threats to the success of plantation forestry in the tropics if they are not monitored and managed properly. Several insect pests recorded in forest plantations, including the little borer called ambrosia beetles (Nair, 2007). Ambrosia beetles are a diverse group of wood-boring insects that play a significant role in forest ecosystems worldwide. These beetles belong to the Curculionidae family in the Coleoptera order, found in either the Scolytinae or Platypodinae subfamilies of weevils, exhibit an obligatory association with nutritional fungal symbionts (Hulcr et al., 2015). While many ambrosia beetles are harmless with minimal economic impact as wood-boring insects, certain species exhibit invasive tendencies and can inflict severe damage on trees (Hulcr et al., 2007). Most ambrosia species prefer to infest dead or dying trees, though some pose a threat to living, healthy trees (Sittichaya et al., 2019). These beetles create tunnels within the xylem, where they introduce symbiotic fungi, commonly known as “fungus-farming beetles” due to their symbiotic relationships with fungi, bacteria, and yeast. This association can lead to plant diseases, often resulting in wilting and eventual death (Tarno et al., 2016).

Scolytinae is the most encountered among these groups, while Platypodinae is less prevalent (Kirkendall et al., 2015). Over 6,000 species of Scolytinae and approximately

1,400 species of Platypodinae are documented, with most native to tropical or subtropical regions (Kirkendall et al., 2015). Ambrosia beetles play a vital ecological role, primarily serving as wood decomposers in forest ecosystems. Their adaptive nature enables them to thrive in diverse climates and habitats. In Southeast Asia, Beaver and Browne (1975) initially recorded 33 Xyleborini species in northern Thailand, but later research, such as Sittichaya et al. (2019), expanded this to 156 species. Beyond Thailand, studies in Indonesia found nine ambrosia beetle species in teak plantations, with *Xylosandrus crassiusculus* dominating in both monoculture and polyculture systems (Setiawan et al., 2018). While ambrosia beetles play roles in temperate ecosystems, they also cause economic losses (Lindgren & Raffa, 2013) attacking diverse forest plants and leading to tree mortality in natural and urban areas (Nair, 2007). Notably, *Euplatypus parallelus* infests Angsana trees in southern Thailand and Malang, Indonesia (Bumrungsri et al., 2008; Tarno et al., 2014), while *X. crassiusculus* and *X. germanus* threaten chestnut trees in Tennessee (Gugliuzzo et al., 2021; Oliver & Mannion, 2001). These invasions underscore broader forestry and horticultural concerns.

1.2 Problem Statement

In Sarawak, ambrosia beetles were observed infesting *Acacia* spp. and *Eucalyptus pellita* plantations. However, ecological studies on ambrosia beetles within Sarawak's forest plantations remain limited. The ambrosia beetles of Sarawak's forest plantations embody a unique component of the region's biodiversity. These beetles, known for their intricate symbiotic relationships with fungi, play a pivotal role in the ecological processes of forest ecosystems. However, the complexity of their ecological interactions and the subtleties of their species-specific characteristics are poorly understood. This is particularly true in the context of Sarawak, where the dearth of ecological studies on ambrosia beetles creates a significant gap in our knowledge. Moreover, the lack of established baseline data for species identification further exacerbates the challenge of understanding these organisms' ecological roles and conserving the biological richness they contribute. Thus, this research aims to fill these gaps by studying ambrosia beetles more closely, helping to support conservation efforts that protect Sarawak's forest ecosystems.

1.3 Objectives

This study aims:

1. To identify the diversity of ambrosia beetles across different forest plantation sites in the western region of Sarawak.
2. To assess the morphological variations among ambrosia beetle species within Sarawak's forest plantation.

1.4 Justification of Study

The review of existing literature reveals significant gaps in the understanding of ambrosia beetle diversity, distribution, and ecological roles within Sarawak. While extensive studies have been conducted in other regions of Southeast Asia, such as Thailand and Indonesia, there remains a lack of localised data specific to Sarawak's unique forest ecosystems. Critical areas requiring further exploration include the species composition of ambrosia beetles, their host preferences, and the influence of plantation types (e.g., monoculture versus polyculture) on their diversity and morphology. Additionally, the potential interactions between ambrosia beetles and other forest pests, such as *Zeuzera coffeae*, remain underexplored, leaving a gap in understanding the broader implications for forest health and productivity in Sarawak.

This study is essential to addressing these knowledge gaps and providing a baseline understanding of ambrosia beetles in Sarawak's forest plantations. By systematically documenting beetle diversity and analysing their morphological variation, the research aims to fill critical voids in the literature while shedding light on how different plantation types influence these ecologically significant insects. The findings will offer valuable insights for forest management, aiding in the development of pest monitoring and control strategies to mitigate potential threats to timber production and biodiversity conservation.

Moreover, as Sarawak is recognised as a biodiversity hotspot, this study contributes to broader conservation efforts by enhancing our understanding of how ambrosia beetles interact with their environment. The data generated will serve as a foundational reference for future studies, informing sustainable plantation practices and fostering regional collaboration in entomological research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews the current body of literature concerning ambrosia beetle taxonomy, biology, morphology, symbiotic associations, and their ecological and economic roles. A particular emphasis is placed on understanding their life history strategies, morphological adaptations, and ecological impacts within forest ecosystems. In addition, the chapter explores documented global diversity and factors shaping ambrosia beetle distribution, including forest management regimes and environmental variables.

Ambrosia beetles, though diminutive in size, represent a group of insects of significant ecological and economic relevance. Their intricate biology, obligate fungal symbiosis, and complex reproductive strategies underpin their successful colonisation of a wide range of habitats, from pristine rainforests to intensively managed plantation systems. These beetles, belonging to the subfamilies Scolytinae and Platypodinae within the Curculionidae family, are best known for their wood-boring behaviour and the cultivation of symbiotic fungi within their galleries, traits that distinguish them from other bark beetles.

While ambrosia beetles are well-studied in parts of Southeast Asia, such as Thailand and Indonesia, a critical knowledge gap remains concerning their presence and ecological roles in Sarawak. The literature review also highlights existing gaps specific to Sarawak's forest plantations, providing justification for this study, which aims to address the scarcity of local data on beetle diversity, host associations, and morphological differentiation. This review serves as a foundation for the subsequent empirical investigations undertaken in this research.

2.2 Overview of Ambrosia Beetles

2.2.1 Taxonomy and Classification

The evolution of bark and ambrosia beetles is linked to their adaptation to life under bark, a strategy that evolved multiple times among weevils to escape hazards like predators and extreme environmental conditions (Gillett et al., 2014; Haran et al., 2013; Jordal et al., 2011). This wood-boring habit likely developed from an ancestral habit of feeding on green leaves (Kirkendall et al., 2015). The closest match is the genus *Camptrocerus*, where adults feed on green leaves before tunneling into the bark to breed (Smith & Cognato, 2011). Building on their ancestral traits, ambrosia beetles have evolved into a specialised group of wood-boring weevils, defined not by a single taxonomic lineage but by their unique ecological strategy (Kirkendall et al., 2015; Hulcr et al., 2015). These beetles belong to the family Curculionidae within the order Coleoptera, commonly recognised as weevils. Within this diverse family, ambrosia beetles are classified under two primary subfamilies: Scolytinae and Platypodinae (Hulcr et al., 2015). These subfamilies exhibit distinct evolutionary traits, including wood-boring behaviour and symbiotic relationships with fungi, which set them apart from other members of Curculionidae (Kirkendall et al., 2015).

Historically, bark and ambrosia beetles were treated as two separate families, Scolytidae and Platypodidae, largely due to their distinctive morphology and specialised wood-boring life histories (Wood, 1982). However, advances in phylogenetic systematics integrating both morphological and molecular evidence have demonstrated that these groups are nested within the true weevils (family Curculionidae) (Farrell et al., 2001; McKenna et al., 2009). Although Scolytinae and Platypodinae exhibit striking morphological and ecological similarities, including cylindrical body form, tunnel architecture, fungal symbiosis, and comparable mating systems, these similarities are largely the result of convergent evolution associated with wood-boring and ambrosial lifestyles (Kirkendall et al., 2015; Hulcr et al., 2015). Modern classification therefore, recognises Scolytinae and Platypodinae as subfamilies within Curculionidae rather than independent families, reflecting their evolutionary relationships and monophyletic placement within the weevils. These subfamilies exhibit distinct evolutionary traits, including wood-boring behaviour and symbiotic relationships with fungi, which set them apart from other members of Curculionidae (Kirkendall et al., 2015).

The Scolytinae subfamily, commonly called bark beetles, is an exceptionally diverse group within the Curculionidae family, encompassing over 3,000 identified species (Hulcr

et al., 2015). These beetles are globally distributed and exhibit specialised adaptations for boring into tree bark and xylem. This behaviour has allowed them to play a crucial ecological role in forest ecosystems by contributing to nutrient recycling, tree population dynamics, and habitat formation for other organisms. Many species within Scolytinae depend on a symbiotic relationship with fungi, which provides nutritional support and facilitates their wood-boring lifestyle (Six, 2012).

The evolutionary history of Scolytinae highlights their origin from bark beetle ancestors, with multiple independent transitions to fungus farming, occurring more than ten times within the subfamily (Jordal & Cognato, 2012). This has resulted in diverse ecological strategies and complex interactions with their environment. Notable genera within Scolytinae include *Xylosandrus*, *Xyleborus*, and *Trypodendron*. These genera include species that are ecologically significant and, in some cases, invasive, causing substantial economic impacts in forestry and agriculture (Hulcr & Stelinski, 2017).

The Platypodinae subfamily, while less diverse than Scolytinae, is equally fascinating. Nearly all members of this group are ambrosia beetle species, with only a few basal taxa retaining a different ecological strategy (Jordal, 2015). Currently, there are approximately 1,400 known species, and it is estimated that these beetles have been cultivating fungi for over 100 million years (Jordal & Cognato, 2012; Vanderpool et al., 2018). These beetles are distinguished by their specialised morphology, particularly adaptations that enhance their ability to transport and cultivate symbiotic fungi. This includes features like mycangia, specialised structures for carrying fungal spores, which play a pivotal role in their survival and reproduction (Batra, 1963; Beaver, 1989). The evolution of mycangia is closely linked to the symbiotic relationship between ambrosia beetles and their fungal partners, allowing these beetles to establish and maintain fungal gardens within their galleries (Kirkendall et al., 2015; Six, 2003). These morphological adaptations are crucial not only for the beetles' lifecycle but also for the ecological roles they play in nutrient cycling and forest dynamics.

Unlike Scolytinae, Platypodinae beetles are thought to have evolved from phloem-feeding weevils, marking a distinct evolutionary pathway (Jordal, 2015). While both subfamilies share a reliance on fungi, Platypodinae species often display more refined fungal symbiosis strategies and morphological differences, such as slender bodies and elongated legs, which are better suited to their specific ecological niches (Kirkendall et al., 2015). Key genera within Platypodinae, though fewer in number, are equally important in understanding

the group's ecological roles and evolutionary history.

Phylogenetic studies reveal that ambrosia beetles evolved independently within these two subfamilies, indicating convergent evolution driven by their shared ecological niche (Farrell et al., 2001; Hulcr et al., 2015). Fossil evidence places the origins of Scolytinae around 90–120 million years ago, with adaptations such as wood-boring and fungal symbiosis arising as strategies to exploit woody habitats and escape predators or environmental stressors (Hulcr & Skelton, 2023).

Accurate classification of ambrosia beetles is critical for understanding their ecological roles, evolutionary history, and impacts on forest ecosystems. Taxonomic studies aid in identifying invasive species, monitoring biodiversity, and developing management strategies. This classification provides a foundation for exploring the unique morphological and ecological adaptations that define ambrosia beetles.

2.2.2 Biology and Life Cycle

Ambrosia beetles exhibit unique biological traits, with their life cycle intricately linked to their symbiotic fungi. Typically, adult females initiate colonisation by boring into weakened or dying trees, where they establish galleries and introduce fungal spores carried in specialised structures called mycangia (Hulcr et al., 2015). These fungi rapidly colonise the gallery walls, producing a nutrient-rich substrate essential for larval development (Biedermann & Taborsky, 2011). Unlike most wood-boring insects, ambrosia beetle larvae feed exclusively on fungal spores and hyphae rather than consuming the wood itself, making this mutualistic association obligatory for survival (Hulcr & Stelinski, 2017).

2.2.2.1 Life cycle Stages

The life cycle of ambrosia beetles comprises four main stages: egg, larva, pupa, and adult. Females lay eggs within the galleries, where larvae hatch and begin feeding on the cultivated fungi. Sibling mating is a common reproductive strategy, occurring within the galleries, which leads to high levels of inbreeding (Kirkendall et al., 2015). This strategy allows rapid population growth and facilitates the colonisation of new host trees, significantly contributing to the beetles' ecological success and, in some cases, invasive tendencies.

As the larvae mature, they pupate within the galleries, and the life cycle culminates with the emergence of new adults. These adults disperse to find new host trees, carrying

fungus spores in their mycangia and perpetuating the fungus-farming cycle. In some instances, the symbiotic fungi can be pathogenic to the host tree, causing diseases or even tree mortality, which highlights the significant ecological and economic implications of Ambrosia beetle infestations (Harrington, 2005; Lindgren & Raffa, 2013).

2.2.2.2 Reproductive Behaviours

Ambrosia beetles display diverse reproductive strategies. Inbreeding is the most common, with sibling mating occurring inside galleries before females disperse. This strategy enables rapid population growth, even from a single coloniser, and has independently evolved multiple times in Scolytinae lineages (Kirkendall et al., 2015). However, inbreeding frequency often decreases with latitude and elevation.

Some species practice outbreeding, where females mate with unrelated males. Outbreeding systems may involve monogyny (one female), bigyny (two females), or polygyny (several females with one male), but outbreeding species are less effective colonisers due to Allee effects at low densities (Gascoigne et al., 2009; Kramer et al., 2009).

While these biological and reproductive traits underpin the success of ambrosia beetles, they also shape the species' broader ecological roles. Understanding how these life-history strategies translate into ecosystem functions and forest health impacts is crucial and is discussed in the following section.

2.2.2.3 Fungal Symbiosis in Beetle Nutrition

The obligate mutualism between beetles and fungi is central to their ecology. Fungal spores are carried in species-specific mycangia and deposited in new galleries, where they proliferate and serve as the sole food source for larvae and adults (Harrington, 2005; Mayers et al., 2015). Ambrosia fungi are highly diverse, having evolved from at least seven fungal lineages, particularly the Ophiostomatales and Ceratocystidaceae families (Alamouti et al., 2009). Notable associations include *Raffaelea* species, some of which (e.g., *R. lauricola*) cause serious tree diseases such as laurel wilt (Fraedrich et al., 2008).

2.2.2.4 Fungus-Farming and Parental Care

Ambrosia beetles actively cultivate their fungal gardens. Females maintain galleries by cleaning debris, regulating humidity, and ensuring optimal conditions for fungal growth (Hulcr & Stelinski, 2017). This fungus-farming behaviour ensures a steady food supply and

exemplifies a form of parental care. Successful cultivation of fungi directly influences beetle reproduction and population dynamics (Hulcr et al., 2007).

2.2.3 Ecological Roles of Ambrosia beetles

2.2.3.1 *Decomposition and Nutrient Cycling*

Ambrosia beetles play a vital role in forest ecosystems by aiding the decomposition of dead or decaying wood. Unlike most wood-boring insects that directly feed on wood tissue, ambrosia beetles cultivate symbiotic fungi within their tunnels, which serve as their primary food source. This fungus-farming behaviour allows them to effectively break down woody substrates, facilitating the release of nutrients back into the soil and contributing to nutrient cycling. Their activity promotes forest health by decomposing organic material, enhancing soil fertility, and sustaining the broader ecosystem (Wood, 2007).

2.2.3.2 *Fungal Symbiosis as an Ecological Strategy*

Their mutualism with fungi benefits both partners: beetles rely on fungi for food, while fungi depend on beetles for dispersal and colonisation. This relationship has evolved multiple times and contributes to fungal biodiversity in forest ecosystems (Alamouti et al., 2009; Schedl, 1958; Vanderpool et al., 2018; Wood, 1982).

2.2.3.3 *Impacts on Forest Health*

Although they contribute to ecosystem balance under natural conditions, ambrosia beetles can negatively impact forest health when populations expand, or invasive species are introduced. Dense infestations may introduce pathogenic fungi, leading to xylem blockage, impaired water transport, and tree mortality. Examples include *Coptoborus ochromactonus* in Ecuador, linked to *Fusarium*-associated mortality in balsa (Stilwell et al., 2014) and *Xyleborus glabratus* in the United States, vector of *Raffaelea lauricola* causing laurel wilt (Hanula et al., 2008). Such cases highlight the dual ecological role of ambrosia beetles, acting both as recyclers of organic matter and as agents of forest decline (Tarno et al., 2016).

2.2.4 Ambrosia Beetles as Pests

2.2.4.1 *Global Economic and Ecological Impacts*

Ambrosia beetles are recognised globally as significant pests due to their adaptability

to diverse environments and their ability to affect both natural forests and managed landscapes. Historically, their impact was viewed largely in terms of lumber degradation rather than the health of living trees. For example, *Trypodendron* species, distributed widely across the Northern Hemisphere, infest freshly felled conifer logs rather than live hosts (Kühnholz et al., 2021). Their colonisation results in extensive gallery perforations and fungal staining, leading to substantial depreciation of timber quality and market value. In fact, the financial losses attributed to this staining can exceed those caused by bark beetle species that directly kill trees (Lindgren & Fraser, 1994).

Over time, the pest importance of ambrosia beetles has expanded beyond wood quality reduction to direct ecological and agricultural consequences. Certain species are highly sensitive to stress-induced volatiles, particularly ethanol, which signals compromised host health. *Xylosandrus crassiusculus*, native to Southeast Asia, has become one of the most problematic ambrosia beetles worldwide due to this attraction mechanism. It attacks a broad range of hosts, thriving both in monoculture and polyculture plantations, and has been reported as a serious pest not only in Asia but also in the United States and parts of Europe, where it impacts hardwood trees, orchards, and ornamental species (Hulcr et al., 2007; Ranger et al., 2010; Setiawan et al., 2018). In plantation forestry, infestations may contribute to reduced productivity through stem boring, fungal infection, and stress-induced mortality (Hulcr & Stelinski, 2017; Ranger et al., 2015). In agroforestry and orchard systems, ambrosia beetles such as *Xylosandrus compactus* and *Xyleborus glabratus* affect fruit-bearing species, including coffee and avocado, thereby extending economic losses across forestry and agricultural sectors (Greco & Wright, 2015; Evans et al., 2010).

2.2.4.2 Examples of Pest Species and Regions Affected

Numerous ambrosia beetle species have emerged as globally important pests. *Xylosandrus crassiusculus* and *X. germanus*, for instance, are invasive in North America and Europe, where they predominantly attack stressed trees and accelerate their decline (Ranger et al., 2015). Another species, *X. compactus*, is notorious for infesting small twigs and shoots of living plants, resulting in branch dieback, deformities, and in severe cases, seedling mortality. This beetle, originally from Southeast Asia, is now widespread in tropical and subtropical regions, including Africa and South America. In coffee plantations, *X. compactus* is of particular concern, causing significant losses to production and quality of beans (Greco & Wright, 2015; Urvois et al., 2021).

In addition to damaging stressed or dead trees, certain invasive ambrosia beetles can threaten healthy, living trees under specific conditions. For instance, *Xyleborus glabratus*, the vector for the fungal pathogen *Harringtonia lauricola*, is responsible for laurel wilt disease in the Lauraceae family. This disease has caused extensive losses in avocado groves in South Florida, representing one of the most economically impactful cases of ambrosia beetle activity (Evans et al., 2010). While laurel wilt also occurs in Asia, its intensity is far lower there (Hulcr et al., 2017).

Other species, such as those in the *Euwallacea* genus, are particularly concerning for their association with fungi from the ambrosial *Fusarium* clade (AFC). *Euwallacea validus* and *E. interjectus* attack living trees already weakened by pre-existing pathogens, further complicating tree health management (Wang et al., 2021). These beetles often signal underlying stress or disease in trees rather than acting as primary agents of decline. As Hulcr and Skelton (2023) note, diagnosing tree health issues involving ambrosia beetles requires a nuanced understanding of their role as one of several stressors.

Within Malaysia and Borneo, information on the economic and ecological impacts of ambrosia beetles remains comparatively limited, particularly in plantation forestry systems. Nevertheless, ambrosia beetles have been reported from both natural forests and commercial plantations, including *Acacia* and *Eucalyptus* stands, where species such as *X. crassiusculus* and *Xyleborus affinis* have been recorded (Beaver & Browne, 1975; Hulcr et al., 2007). In Malaysia, reports from Peninsular plantations and Sabah indicate that ambrosia beetles frequently colonise stressed or recently felled timber, contributing to wood staining and reduced timber value. However, comprehensive documentation of species diversity, host associations, and pest severity in Sarawak's plantation landscapes remains scarce. This regional gap highlights the need for systematic assessment of ambrosia beetle communities within Sarawak's forest plantations.

2.2.4.3 Invasive Pathways, Quarantine, and Risk Management

The globalisation of trade and the increased movement of timber, nursery stock, and wooden packaging materials have accelerated the spread of ambrosia beetles outside their native ranges (Marini et al., 2011). Because many species are small, cryptic, and capable of surviving in concealed life stages within wood products, they often evade early detection (Hulcr et al., 2017). Once introduced, ambrosia beetles can establish rapidly, particularly in disturbed or monoculture environments where suitable hosts are abundant (Kirkendall et al., 2015; Hulcr & Stelinski, 2017). Invasive species, such as *X. crassiusculus*, *X. germanus*,

and *X. glabratus*, exemplify this pathway, having expanded their ranges across multiple continents and caused severe ecological and economic consequences (Hulcr et al., 2017).

To mitigate these risks, international phytosanitary measures play a critical role. Standards such as ISPM-15, which mandate heat treatment or fumigation of wooden packaging, are designed to reduce the likelihood of pest introductions. However, interceptions at ports continue to highlight the persistence of this pathway (Gomez et al., 2018). In regions with expanding plantation forestry, such as Sarawak, risk management requires not only compliance with international standards but also the establishment of domestic early detection networks. Ethanol-baited traps and sentinel plantings have proven effective tools for monitoring potential invasions.

Equally important are preventive strategies within plantations and nurseries. Diversifying planting systems, maintaining buffer zones, and reducing host stress through silvicultural practices can lower susceptibility to ambrosia beetle outbreaks. Integrating morphological and ecological monitoring with molecular or symbiont screening further strengthens the capacity to detect cryptic invasive species. Ultimately, incorporating ambrosia beetles into broader invasive species risk assessments is essential for safeguarding both exotic plantation resources and indigenous biodiversity in Sarawak and beyond. In Sarawak, large-scale ambrosia beetle outbreaks have not been widely documented in published literature; however, preventive strategies are embedded within broader forest health monitoring and plantation management frameworks implemented by the Forest Department Sarawak and licensed planted forest holders. Routine pest surveillance, sanitation felling of stressed or diseased trees, compliance with phytosanitary regulations for timber movement, and site-level monitoring through field inspections constitute primary preventive measures. In addition, plantation management practices that reduce host stress, such as appropriate spacing, thinning regimes, and site maintenance, serve as indirect but important mitigation strategies. While these measures are not always ambrosia beetle-specific, they contribute to lowering outbreak risk in plantation systems.

2.3 Diversity of Ambrosia Beetles

2.3.1 Documented Diversity

Ambrosia beetles represent one of the most diverse and ecologically significant groups of insects, with approximately 7,400 described species (6,000 Scolytinae and 1,400 Platypodinae) globally (Kirkendall et al., 2015). These beetles thrive in a wide range of habitats due to their unique symbiosis with fungi, which they cultivate and depend on for nutrition. This fungal relationship has facilitated their adaptation and proliferation across diverse ecosystems.

Southeast Asia, recognised as a biodiversity hotspot, offers rich insights into ambrosia beetle diversity. Early work by Beaver and Browne (1975) in Thailand recorded 33 species of Xyleborini, primarily in the northern regions. Over the years, further studies have substantially expanded the known diversity. Sittichaya et al. (2019) recorded 156 species of Xyleborini in Thailand, highlighting the diversity of these beetles. Similarly, studies in Indonesia have reported nine species of ambrosia beetles in teak plantations, with *X. crassiusculus* emerging as the dominant species in both monoculture and polyculture systems (Setiawan et al., 2018).

Research in other regions underscores the diversity of ambrosia beetles. In Papua New Guinea, Hulcr et al. (2007) identified 84 morphospecies from over 12,000 individuals in lowland rainforests, revealing that tree part type, rather than geographical location, had a greater influence on beetle community composition. Similarly, Dole et al. (2021) canopy fogging in the Ecuadorian Amazon revealed 121 species of ambrosia beetles, highlighting their remarkable diversity and habitat adaptability.

These studies highlight the value of using different methods, such as ethanol-baited traps and canopy fogging, to explore the diversity of ambrosia beetles. Compared to other regions in Southeast Asia, information on ambrosia beetle diversity in Sarawak remains limited and fragmented. Existing records largely originate from general forest insect surveys and plantation pest surveillance rather than dedicated taxonomic or ecological studies. Although ambrosia beetles have been reported from exotic plantations such as *Acacia mangium*, *A. crassicarpa*, and *Eucalyptus pellita* in Sarawak, comprehensive species inventories are still lacking (Erica et al., 2024). However, there is still limited information on species diversity and ecological roles in areas like Western Sarawak, showing the need for further studies.

2.3.2 Factors Influencing Diversity

The diversity and distribution of ambrosia beetles are significantly shaped by environmental factors such as climate, habitat type, and forest management practices (Kirkendall et al., 2015; Hulcr & Stelinski, 2017). For instance, in Indonesia, Tarno et al. (2022) found that protected pine forests supported the highest diversity and abundance of ambrosia beetles, with 13 species recorded. In contrast, agroforestry systems exhibited significantly lower diversity, with only seven species. This suggests that undisturbed environments with minimal human intervention provide ideal conditions for beetle biodiversity.

Hulcr et al. (2007) also noted that tree species diversity is less critical than forest stability and structural heterogeneity in supporting ambrosia beetle populations. The findings from studies in Papua New Guinea and the Ecuadorian Amazon further emphasise the importance of habitat stability and environmental variables such as stand age, humidity, and temperature. Tarno et al. (2022) observed positive correlations between stand age and humidity with beetle species diversity, while higher temperatures negatively impacted populations.

Polyculture and agroforestry systems, which involve greater disturbance and human activity, generally show reduced beetle diversity compared to monoculture plantations. Martínez et al. (2019) reported that natural forests with higher ecological and structural complexity provided more niches for ambrosia beetles than balsa plantations, illustrating the influence of habitat type on beetle diversity.

2.3.3 Biogeographical and Habitat Patterns of Diversity

Globally, patterns of ambrosia beetle diversity vary strongly with biome and land use. Tropical regions, including Southeast Asia, Africa, and the Neotropics, harbour the greatest species richness, often with high levels of endemism (Hulcr et al., 2007; Dole et al., 2021). In contrast, temperate regions generally support fewer species but may experience dominance of invasive taxa such as *Xylosandrus germanus* in Europe and *X. crassiusculus* in the United States (Ranger et al., 2015). Island ecosystems, such as those in Papua New Guinea and the Pacific, hold tremendous ambrosia beetle diversity but are still under-sampled, often yielding taxa recognized only as morphospecies. For example, Hulcr et al. (2007) recorded 84 distinct morphospecies from over 12,700 individuals in lowland rainforests of Papua New Guinea. More recently, Dole et al. (2021) documented more than

400 scolytine morphospecies from their samples, many of which were rare, underscoring both the richness and the unresolved taxonomy of beetle assemblages in tropical islands.

Comparisons between natural and managed habitats further highlight the influence of disturbance on diversity. Plantation forests, particularly monocultures, tend to support lower overall diversity while promoting the dominance of a few disturbance-tolerant generalists such as *X. crassiusculus* (Setiawan et al., 2018; Martínez et al., 2019). In contrast, natural forests and polyculture systems provide structurally complex habitats that offer a greater range of ecological niches, thereby sustaining higher species richness and reducing dominance effects. These contrasts underscore the ecological costs of converting natural forests to simplified production systems, where biodiversity is lost and pest risk is heightened.

Despite increasing studies, knowledge gaps remain substantial. Much of the available information is biased toward ethanol-baited trapping, which disproportionately attracts certain taxa while overlooking canopy specialists or species confined to small woody substrates. Furthermore, rapid land-use change, and climate variability are likely to alter community structure in poorly understood ways, raising concerns over both biodiversity conservation and forest health. Addressing these gaps is particularly urgent in regions such as Western Sarawak, where industrial plantation forestry is expanding, yet systematic data on ambrosia beetle diversity remain sparse.

While studies of diversity reveal patterns of species richness, distribution, and community composition, they often fall short in distinguishing closely related or cryptic taxa. For this reason, morphological analysis remains essential, providing trait-based evidence for accurate identification and for detecting subtle variation within and among species. Morphological adaptations also contribute directly to the survival and ecological success of ambrosia beetles in different environments. For example, species such as *Xylosandrus discolor* and *Scolytoplatypus* sp. occur exclusively in protected pine forests, suggesting that they possess traits finely tuned to stable and less disturbed habitats (Tarno et al., 2022). When combined with diversity assessments, morphological investigations strengthen species delimitation, clarify ecological adaptations, and ultimately deepen our understanding of the evolutionary and ecological dynamics shaping ambrosia beetle assemblages.

2.4 Morphology of Ambrosia Beetles

2.4.1 General Morphological Traits

Ambrosia beetles display distinct physical characteristics as shown in Table 2-1, tailored to their ecological roles as wood borers and fungus farmers. They are generally small, ranging from 1 to 5 mm in length, with some species growing larger under favourable environmental conditions. Their compact, cylindrical bodies are highly specialised for boring into wood, enabling them to establish intricate tunnel systems where they cultivate symbiotic fungi. Ambrosia beetles exhibit less variation in body size compared to bark beetles, a feature attributed to their dependence on nutrient-rich fungal matter rather than the variable nutrition found in tree tissues (Haack & Slansky, 1987; Kirkendall, 1983).

Table 2-1:
The morphological traits across different body parts of the beetles, including the head, antennae, pronotum, legs, elytra, and elytral declivity that are commonly used for the identification of ambrosia beetle.

Morphological Character	Description	Examples	Reference
Head (Frons)	Hooded or convex, often adorned with punctures and setae.	<i>Xyleborinus elongatus</i>	Hulcr et al., (2020); Reding & Ranger, (2020)
Antennae	Geniculate with distinct club shapes; variations in shape and setae distributions.	<i>Xyleborus saxesenii</i>	Gomez et al. (2018); Rabaglia et al. (2006)
Pronotum	Features transverse asperities on the anterior slope; sparsely punctured disc; shape varies by species.	<i>Cnestus mutilatus</i> , <i>X. elongatus</i>	Hulcr & Stelinski (2017); Rabaglia et al. (2006)
Elytra	Elongate, cylindrical, punctate-striate; interspersed with setae.	<i>Xyleborinus saxesenii</i>	Hulcr & Stelinski (2017)
Elytral Declivity	Varies in granulation, spines, or ridges; used for diagnostic purposes.	<i>Xyleborus caledoniae</i> , <i>X. saxesenii</i>	Gomez et al. (2018); Hulcr et al. (2020)
Sexual Dimorphism	Females larger, flight-capable; males smaller, flightless, lighter coloration.	<i>Xylosandrus crassiusculus</i>	Hulcr et al. (2020); Rabaglia et al. (2006)

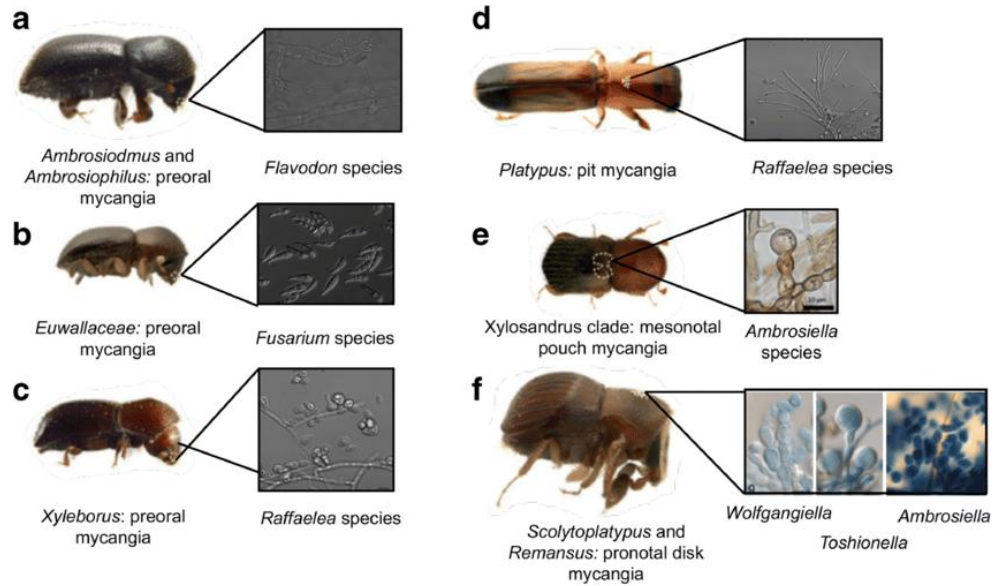
Morphological differences between the Scolytinae and Platypodinae subfamilies reflect their evolutionary adaptations. Scolytinae beetles tend to have shorter, robust bodies with rounded heads suited for tunneling into sapwood. In contrast, Platypodinae species, also known as pinhole borers, are slenderer and more elongated, with larger mandibles that enable them to penetrate denser wood. These adaptations highlight the ecological niches each subfamily occupies, from decomposing material to live, dense wood. Colouration among ambrosia beetles ranges from reddish-brown to nearly black, aiding in camouflage within their habitats. However, factors such as age, preservation methods, and environmental conditions can also influence colouration.

2.4.2 Specialised Features for Fungal Symbiosis

Ambrosia beetles possess unique morphological adaptations to maintain their obligate relationship with fungi. Mycangia, specialised structures for carrying fungal spores, are a key feature that allows beetles to introduce their symbiotic fungi into new habitats. These structures, often located near the mandibles or on the thorax, vary in size and complexity among species. Additionally, their hardened elytra protect the beetles' wings and bodies, sealing them against moisture loss and external pressures within their tunnels (Haack & Slansky, 1987).

The thorax and mandibles are also highly adapted for their wood-boring lifestyle. Robust exoskeletons support powerful muscles for burrowing, while modifications in the mandibles enhance their efficiency in excavating wood and preparing galleries for fungal cultivation. These morphological traits collectively enable ambrosia beetles to thrive in their specialised ecological niches.

Figure 2-1:
Diversity of mycangial structures and associated fungal symbionts in ambrosia beetles.



Note: Panels (a–c) illustrate preoral mycangia in selected Scolytinae lineages, including *Ambrosiodmus*, *Euwallacea*, and *Xyleborus*, showing their associated fungal partners. Panel (d) shows pit mycangia in *Platypus* (Platypodinae), while panel (e) illustrates mesonotal pouch mycangia in the *Xylosandrus* clade. Panel (f) depicts pronotal disk mycangia in *Scolytotplatypus* and *Remansus*. These specialised structures facilitate the transport and cultivation of symbiotic fungi within host trees. Adapted from Joseph and Keyhani (2021).

2.4.3 Intraspecific Variation

Environmental conditions, geographic distribution, and habitat quality influence intraspecific morphological variations among ambrosia beetles. Body size, for instance, is largely determined by the quality and quantity of fungal food consumed by larvae during development (Haack & Slansky, 1987). Species such as those within the genus *Xyleborus* exhibit sexual dimorphism, with females typically larger and having more pronounced pronotal features than males (Ospina-Garcés et al., 2021). Additionally, studies have shown that body size may increase with elevation, potentially due to cooler temperatures that prolong larval development and allow greater resource accumulation before pupation, as well as differences in host quality and fungal symbiont performance across altitudinal gradients (Hulcr & Cognato, 2013).

2.4.4 Interspecific Variation

Morphological variation among different ambrosia beetles species forms the foundation of their taxonomy and systematics. Diagnostic traits such as body size, antennal segmentation, pronotal shape, and elytral declivity are commonly used to distinguish species, particularly within diverse genera such as *Xyleborus* and *Xylosandrus* (Wood, 2007). Although body size may exhibit intraspecific plasticity influenced by environmental factors such as elevation or host quality, interspecific differences in size are typically consistent and supported by additional structural characters (Cognato, 2006). Therefore, body size is rarely used as a sole diagnostic feature but rather interpreted in combination with discrete morphological traits in integrative taxonomic frameworks (Wood, 2007). Interspecific variation is especially significant in Scolytine beetles, where cryptic species complexes occur, and morphological characters must often be interpreted alongside molecular data (Cognato, 2006).

Patterns of interspecific variation also reflect ecological adaptations. Closely related species may diverge in body size, gallery architecture, or fungal specificity, enabling coexistence through niche partitioning (Kirkendall et al., 2015). For example, the *Xyleborus ferrugineus* complex has been recognised as a species complex requiring taxonomic resolution, with subtle morphological variation reported among closely related forms (Smith et al., 2020). Such interspecific differentiation not only facilitates taxonomic identification but also enhances understanding of ecological interactions, host associations, and evolutionary relationships within the Scolytinae.

2.4.5 Importance of Morphological Studies

Studying the morphological traits of ambrosia beetles is crucial for species identification, taxonomy, and understanding ecological adaptations. Morphological analyses, often combined with genetic data, have provided valuable insights into the evolutionary relationships and ecological roles of these beetles. For instance, traditional morphometrics (measuring physical traits) and geometric morphometrics (analysing shape variations) have been employed to distinguish closely related species or geographic populations.

Valerio-Mendoza et al. (2017) utilised these methods to examine *Dendroctonus brevicomis*, identifying distinct morphological groups based on antennal and genital

structures. Similarly, studies on the *Euwallacea fornicatus* species complex revealed significant morphological differences in elytral and pronotal dimensions across genetic lineages, emphasising the need for integrated approaches that combine morphology with molecular data (Gomez et al., 2018).

Although global and regional studies have advanced knowledge on ambrosia beetles diversity and morphology, information specific to Sarawak remains limited. Examining the status of ambrosia beetles in this region is therefore necessary to contextualise their ecological roles, potential impacts, and management challenges within local forest plantation systems.

2.5 Ambrosia Beetles in Sarawak

2.5.1 Current Knowledge Gaps

Despite the growing body of research on ambrosia beetles across Southeast Asia, studies specifically focused on Sarawak remain sparse. The region's rich forest biodiversity, encompassing a mix of monoculture and polyculture systems, presents a unique opportunity to explore ambrosia beetle diversity and their ecological roles. However, detailed data on species composition, host specificity, and ecological dynamics in Sarawak's forest plantations are lacking. This gap in knowledge highlights the need for localised studies to understand the interactions between ambrosia beetles, their host trees, and the surrounding environment.

2.5.2 Potential Ecological and Economic Impacts in Sarawak

Based on insights from other regions, ambrosia beetles in Sarawak could have significant ecological and economic impacts. Their symbiotic relationship with fungi, while critical to their survival, may pose a threat to forest health when beetle populations proliferate. Infestations can disrupt tree growth and, in severe cases, lead to mortality. In commercial plantations, this could reduce timber yield and quality, particularly for economically important species like *Acacia* spp. and *E. pellita*. Furthermore, the introduction or spread of non-native ambrosia beetle species could have cascading effects on Sarawak's

native biodiversity, potentially altering ecosystem dynamics and increasing pest management challenges.

2.5.3 Known Host Species in Sarawak

Although comprehensive host records for Ambrosia beetles in Sarawak are limited, several commercially important tree species have been identified as hosts. *Acacia* spp. and *Eucalyptus pellita* are among the known hosts, making them particularly vulnerable in plantation settings. In the case of *Eucalyptus pellita*, infestations by *Zeuzera coffeae*, a significant stem borer in tropical plantation systems (Kalshoven, 1981; Hill, 2008), may indirectly influence ambrosia beetle populations by increasing host stress and altering wood conditions. As Sarawak continues to expand its forest plantations, understanding host preferences and beetle behaviour will be crucial for developing sustainable forest management practices and mitigating potential pest outbreaks.

These host associations, combined with the ecological and economic implications of ambrosia beetles in Sarawak, emphasise the urgent need for systematic research. To address the identified gaps, a structured analytical framework is required, one that integrates measures of diversity and assessments of morphological variation in line with the objectives of this study.

2.6 Analytical Framework for Diversity and Morphological Variation

Morphological and ecological studies often combine measures of diversity with statistical analyses to provide a comprehensive understanding of population structure and variation. Diversity indices such as the Shannon–Wiener index (H'), Simpson's index (D), and Evenness (E) are widely used to quantify species richness and relative abundance in ecological communities (Magurran, 2021). These indices provide baseline information on community composition and are frequently applied in insect studies to compare diversity across habitats, disturbance gradients, or host plant associations (Gotelli & Colwell, 2001).

At the trait level, univariate analyses such as the Kruskal–Wallis test (H) and Chi-square (χ^2) are commonly used to detect significant differences in individual morphological features among groups, particularly when data deviate from normality and parametric assumptions fail (Zar, 2010). In entomological research, Kruskal–Wallis tests have been effectively used to assess morphological variation across species using non-parametric data, while Chi-square analyses are commonly applied to evaluate categorical behavioural and

ecological variables (Zar, 2010; Sontigun et al., 2017).

Beyond single-trait comparisons, multivariate approaches provide a holistic view of morphological variation by incorporating multiple variables simultaneously. Principal Component Analysis (PCA) is widely applied to summarise variance in quantitative traits and identify the most informative dimensions of interspecific differences, while Principal Coordinates Analysis (PCoA) is particularly suited for qualitative and binary-coded traits, allowing for the visualisation of species clustering based on categorical characters (Klingenberg, 2010). Such ordination techniques are especially effective for species delimitation, evaluating intraspecific variation, and detecting cryptic taxa (Adams et al., 2013).

To statistically validate groupings, PERMANOVA (Permutational Multivariate Analysis of Variance) has emerged as a robust non-parametric alternative to MANOVA for testing differences in multivariate trait datasets (Anderson, 2001). Complementary methods such as SIMPER (Similarity Percentage Analysis) identify which traits contribute most to between-group dissimilarities, thereby aiding in the biological interpretation of results (Clarke, 1993).

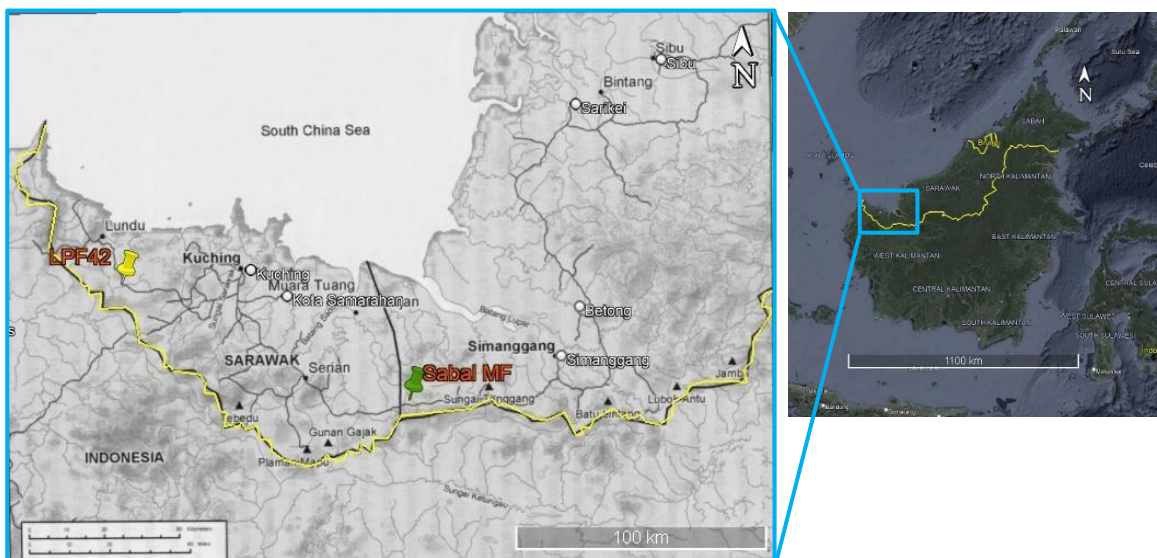
In Ambrosia beetle research, these approaches have proven especially valuable. Landi et al. (2017) demonstrated morphological conservatism in *X. crassiusculus* across South and North America, showing stability in both morphological and molecular characters. In contrast, Ospina-Garcés et al. (2021) used geometric morphometrics to document sexual dimorphism and morphological integration in *Xyleborus affinis*, highlighting how shape differences in the pronotum and elytra are linked to dispersal roles. Likewise, Mandelshtam and Petrov (2017) successfully applied multivariate methods to discriminate closely related scolytine beetles. Collectively, the integration of univariate and multivariate approaches supported by diversity indices provides a robust framework for evaluating both ecological diversity and morphological differentiation in ambrosia beetles.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Study Area

The study was conducted in two forest plantation sites in western Sarawak: Licence Planted Forest 42 (LPF42) in Sampadi, Lundu, and the Sabal Forest Reserve (Sabal FR), Simunjan (Figure 3-1). These sites were selected to assess ambrosia beetles' diversity and morphological variation across distinct plantation types and tree species compositions.

Figure 3-1:
The study sites for ambrosia beetles' trapping in Western Sarawak



Source: Photo derived from Google Earth Pro Software

Figure 3-2 (a & b) presents an overview of the selected plots at the two study sites, LPF42 (Sampadi, Lundu) and Sabal Forest Reserve (Simunjan), showing representative views of the plantation conditions where ambrosia beetle trapping was conducted. The two study sites, LPF42 and Sabal FR, were selected to represent contrasting forest plantation contexts in western Sarawak. LPF42 is an industrial forest plantation dominated by exotic tree species and managed under a production-oriented planting system. In contrast, Sabal FR represents a conservation-focused plantation landscape with greater structural and compositional heterogeneity.

The GPS coordinates provided for LPF42 (1°30'34.4"N, 109°55'01.4"E) and Sabal FR (1°05'10.5"N, 110°56'12.4"E) represent the central reference point of each study site. Individual plots and transect lines were established within designated plantation compartments under the same management block and were therefore located within close spatial proximity to the recorded site coordinates. As all plots were situated within relatively homogeneous stand conditions, site-level coordinates were considered sufficient to represent the geographic location of the sampling areas.

At LPF42, managed by Polima Forest Bintulu (1°30'34.4"N, 109°55'01.4"E), four plots were selected: three monocultures of *Acacia mangium*, *A. crassicaarpa*, and *Eucalyptus pellita* established in 2015, and one polyculture plot established in 2017 consisting of *A. mangium*, *A. crassicaarpa*, *E. pellita*, *Falcataria moluccana*, and oil palm (Table 3.1). The site is characterised by a relatively uniform understory dominated by ferns, reflecting a simplified habitat structure typical of managed plantation systems (Figure 3.2c).

Sabal FR (1°05'10.5"N, 110°56'12.4"E) comprised four monoculture plots established in 2011 with *Acacia* spp. (hybrid), *A. mangium*, and *E. pellita* (Table 3.1). In contrast to LPF42, Sabal FR contains shrubs and woody vegetation in the understory, providing more heterogeneous microhabitats that are likely to support higher beetle diversity (Figure 3.2d). This site reflects a conservation-focused plantation landscape incorporating both indigenous and hybrid tree species.

The selection of these two sites enabled a comparative assessment of ambrosia beetle diversity, assemblage composition, and morphological variation under differing plantation management regimes, vegetation structure, and understory complexity in western Sarawak.

**Figure 3-2:
Overview of study sites in Western Sarawak**



Note: (a) Overview of an *Acacia crassicaarpa* plantation at Licence Planted Forest 42 (LPF42); (b) Overview of an *Eucalyptus pellita* plantation at Sabal Forest Reserve (Sabal FR); (c) Understory conditions at LPF42 showing a relatively uniform fern-dominated ground layer along transect line TP3; and (d) Understory conditions at Sabal FR along transect line TP1, characterised by the presence of shrubs and woody vegetation.

**Table 3-1:
Plant species and planting date of each trapping plot in LPF42, Sampadi and Sabal
FR, Simunjan**

Study Site	Trapping Transect Line	Host Plant	Year of planting
LPF42	TP1	<i>Acacia mangium</i>	2015
LPF42	TP2	<i>Acacia crassicaarpa</i>	2015
LPF42	TP3	<i>Eucalyptus pellita</i>	2015
LPF42	TP4	<i>A. mangium</i> , <i>A. crassicaarpa</i> , <i>E. pellita</i> , <i>Falcataria molluccana</i> & oil palm trees	2017
Sabal FR	TP1	<i>Acacia</i> spp. (Hybrid)	2011
Sabal FR	TP2	<i>A. mangium</i>	2011
Sabal FR	TP3	<i>E. pellita</i> (Adjacent to wooded forest)	2011
Sabal FR	TP4	<i>E. pellita</i> 2 (Adjacent to <i>A. mangium</i> plot)	2011

Source: Forest Department Sarawak (2020)

3.2 Sampling Methods

A systematic sampling approach was adopted to ensure comprehensive beetle collection across the study plots. Each site featured four transect lines (TP1–TP4), based on species composition as shown in Table 3-1. LPF42 included three monoculture transects (*A. mangium*, *A. crassicarpa*, *E. pellita*) and one polyculture transect. Sabal FR comprised four monoculture transects of *Acacia* hybrid, *A. mangium*, and *E. pellita*. Figure 3-3 shows that the Modified Intercept Panel Traps (MINT PT) used in this study were adapted from Czokajlo et al. (2001).

Figure 3-3:
Modified Intercept Panel Traps (MINT PT)



Notes: Intercept panel trap baited with ethanol used in this study. The trap consists of: (a) the main body constructed from black polypropylene (PP) corrugated sheets arranged in a cross-vane configuration; (b) a sealed ziplock plastic bag containing a sponge saturated with 95% ethanol serving as the attractant; and (c) a collecting container filled with water and a small amount of detergent to retain captured beetles.

MINT PT constructed using 4-mm thick black polypropylene corrugated sheets, the traps consisted of two 54 x 17.5 cm rectangular panels arranged in a cross structure with a 35 cm cap and a soap-filled collecting container below. Traps were baited with 15 mL of ethanol and 25 mL of alpha-pinene (Kelsey et al., 2014; Reding & Ranger, 2020; Setiawan et al., 2018), suspended approximately 1m above ground (Figure 3.4) to mimic beetles' natural attraction to stressed trees, as validated by prior research (Steininger et al., 2015). Each transect line had six MINT PT, arranged along a 100m transect line with traps spaced 20m apart, corresponding to fixed sampling points at 0m, 20m, 40m, 60m, 80m, and 100m. The use of six traps ensured consistent spatial coverage along the entire transect while maintaining equal sampling intervals. Trapping was conducted in January, April, July, and October 2022 at LPF42 and Sabal FR. The trapping periods are summarised in Table 3-2. Traps were checked daily for five consecutive days during each cycle.

Table 3-2:
Trapping periods at LPF42 and Sabal FR in 2022

Month/Year	Location(s)	Duration	Notes
January 2022	LPF42 & Sabal FR	24 – 31 January	Traps checked daily
April 2022	Sabal FR	11 – 14 April	Traps checked daily
April 2022	LPF42	18 – 22 April	Traps checked daily
July 2022	Sabal FR	12 – 15 July	Traps checked daily
July 2022	LPF42	18 – 21 July	Traps checked daily
October 2022	Sabal FR	11 – 14 October	Traps checked daily
October 2022	LPF42	17 – 21 October	Traps checked daily

3.3 Species Identification

Morphological identification was conducted based on established taxonomic keys and diagnostic characters commonly used in Scolytinae (Table 3-3) and Platypodinae (Table 3-4) (Hulcr & Smith, 2010; Smith et al., 2022; Bickerstaff et al., 2019). A total of 170 beetle specimens (129 from LPF42 and 41 from Sabal FR) were subjected to identification and morphometric analysis. Twenty-four (24) morphological traits were assessed for Scolytinae subspecies (5 quantitative; 19 qualitative traits), while eleven (11) morphological traits were examined for Platypodinae (1 quantitative; 10 qualitative traits).

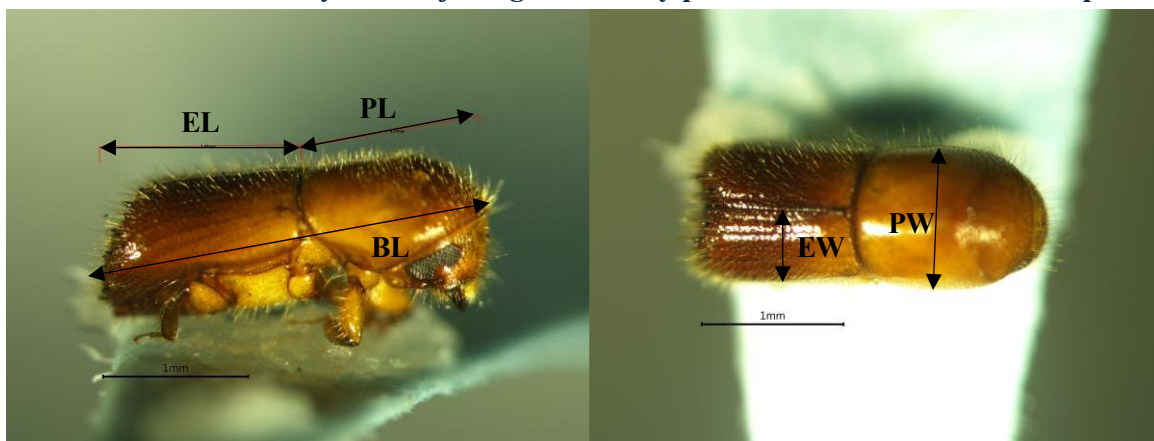
3.3.1 Quantitative Trait Measurement

Key morphological traits for Scolytinae, such as body length (BL), pronotum width (PW), pronotum length (PL), elytral width (EW), and elytral length (EL), as listed in Table

3-3, were measured using high-resolution images captured under an Olympus SZ61 stereomicroscope with subsequent analysis performed using Top View 3.7 software. Meanwhile, for Platypodinae, we only measured the body length (BL) following Brickerstaff et al. (2019). The image includes a scale bar (1 mm) to ensure accurate and standardised measurements across specimens (Figure 3-4 & Figure 3-5). Measurements were taken to the nearest 0.01 mm to ensure precision and reproducibility.

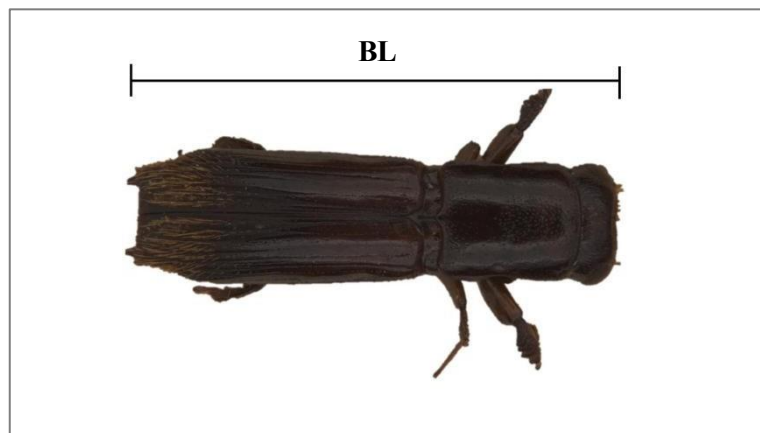
The selection of quantitative traits differed between subfamilies due to differences in taxonomic diagnostic frameworks. For Scolytinae, multiple morphometric measurements (body length, pronotum length and width, elytral length and width) were recorded, as these characters are commonly used in species-level discrimination within morphologically similar taxa (Wood, 1982; Cognato, 2006). In contrast, Platypodinae taxonomy relies predominantly on discrete structural characters, particularly elytral declivity configuration, pronotal carina, and sexually dimorphic traits (Kirkendall et al., 2015). Accordingly, only body length was measured as a general size reference, consistent with established diagnostic protocols. The selected traits represent standard diagnostic characters employed in ambrosia beetle taxonomy, including body size measurements, pronotal structure, antennal club morphology, elytral declivity configuration, vestiture patterns, and tibial dentition.

Figure 3-4:
Measurement of *Xyleborus ferrugineus* body parts under a stereo microscope



Notes: Morphometric parameters measured for Scolytinae specimens. Body length (BL) was measured from the anterior margin of the pronotum to the apex of the elytra; pronotum length (PL) from the anterior to posterior pronotal margins; elytral length (EL) from the elytral base to apex; pronotum width (PW) at the widest point of the pronotum; and elytral width (EW) at the widest point of the elytra. Scale bar = 1 mm.

Figure 3-5:
Measurement of *Xyleborus ferrugineus* body parts under a stereo microscope



Source: This reference image was adapted from Bickerstaff et al. (2019)

3.3.2 Categorical Coding of Qualitative Traits

Each qualitative morphological trait for both Scolytinae (Table 3-3) and Platypodinae (Table 3-4) was assigned discrete numerical codes corresponding to visually distinct character states observed across specimens. For example, pronotum shape (dorsal view) was categorised into eight types (Type 1 to Type 8), with each type assigned a numeric code from 1 to 8. Similarly, tubercle patterns were coded based on their prominence, density, and distribution, while protibiae edge shapes were grouped into distinct structural forms. Certain characters that may appear size-related (e.g., protibial posterior edge development for Scolytinae or frons setae robustness for Platypodinae) were coded as qualitative states following standard taxonomic keys and online diagnostic tools. Although originally described using terms such as “small/large” or “thin/thick,” these represent discrete structural conditions rather than continuous morphometric variables. Classification was based on observable morphological differences under magnification rather than numerical measurement, consistent with traditional ambrosia beetle diagnostic frameworks (Wood, 1982; Kirkendall et al., 2015).

Table 3-3:
List of quantitative and qualitative morphological traits used for Scolytinae morphometric analysis.

No.	Characters	Type	Description
<u>Quantitative</u>			
1.	Body Length (BL)	NA	Measure in millimeters
2.	Pronotum Length (PL)	NA	Measure in millimeters
3.	Pronotum Width (PW)	NA	Measure in millimeters
4.	Elytra Length (EL)	NA	Measure in millimeters
5.	Elytra Width (EW)	NA	Measure in millimeters
<u>Qualitative</u>			
6.	Scutellum (SC)	1	Flush with elytral, flat
		2	Flush with elytra, medially impressed
		3	Conical, surrounded by setae
		4	Depressed below elytra, flat
		5	Narrow, minute, convex, and slightly raised above elytra surface
		6	Not visible from dorsal view
7.	Frons Texture	1	Smooth
		2	Reticulated
8.	Club Shape	1	Approximately circular
		2	Wider than long
		3	Tall. "Telescopic" (Segment nested)
		4	Longer than wider
9.	Pronotum shape, lateral view (PSL)	1	Basic type
		2	Dorsal side uniformly rounded, no clear summit
		3	Pronotum taller than the basic type
		4	Pronotum short and tall
		5	Robust with summit moved anteriorly
		6	Robust, subquadrate or rounded
		7	Pronotal disc concave
10.	Pronotum shape, dorsal view (PSD)	1	Conical
		2	Rounded
		3	Basic, parallel-sided
		4	Subquadrate, anterolateral "corners" slightly prominent
		5	Quadrate, anterolateral "corners" conspicuous, lateral sides almost parallel
		6	Conical, longer than type 1
		7	Conical frontally, angulate
		8	Rounded frontally, longer than the basic type 2
11.	Procoxae Condition (PCC)	1	Type 1: Contiguous
		2	Type 2: Separated
12.	Protibiae edge shape (PTES)	1	Semi-circular with evenly rounded edges
		2	Obliquely triangular, broadest at the apical third of length
		3	Distinctly triangular, slender on the upper part, broad and denticulate on the lower part
		4	Slender, not distinctly flat
13.	Protibiae posterior edge (PTPE)	1	Weakly developed (posterior edge not projecting beyond tibial margin)
		2	Strongly developed (posterior edge distinctly expanded and projecting beyond tibial margin)
14.	Number of protibial socketed denticles (PTSD)	1	Fewer than 6
		2	between 6 and 8
		3	9 or more

Table 3-3: Continued.

No.	Characters	Type	Description
15.	Shape of elytral base (EBS)	1	Straight
		2	Curved
16.	Elytral disc convexity (EDC)	1	Convex
		2	Ascending posteriorly
		3	Flat and transverse
		4	Convex and impressed with a saddle-like depression
17.	Punctures on elytral Disc (EDP)	1	In stria line
		2	Confused
18.	Shape of elytral declivity, lateral view (EDSL)	1	Rounded but steep, especially towards the apex
		2	Slowly descending, often flat
		3	Truncated, sometimes with costa or carina on the edge
		4	Truncated, with teeth or ridges on the edge
		5	The declivity rounded, but the elytral margin emarginate
		6	Excavated
		7	Middle flat, or rounded
		8	Middle flat, or rounded
19.	Shape of elytral declivity, dorsal view (EDSD)	1	Rounded
		2	Angulate
		3	Acuminate
		4	Broad, flattened
		5	Emarginate
		6	Struncated
20.	Vestiture on elytral declivity (EDV)	1	Bald, or almost so
		2	Few setae
		3	Vestiture conspicuously dense or long
		4	Flattened scale-like setae and various types
21.	Tubercle Pattern (TP)	1	No tubercles, or only uniform minutes granules
		2	No tubercles in interstria 1 (sutural), and several tubercles in interstriae 2, 3 and beyond
		3	No tubercles in interstria 2, and several tubercles in interstriae 1, 3 and beyond
		4	Tubercles on elevated costa around the declivity, their assignments to interstriae is difficult
		5	A pair of long projections, one on each elytron
		6	Large tubercles in all interstriae, or different arrangement
		7	Three spines near the elytral margin, the biggest spine near the summit
22.	Striae or interstriae on the upper part of the Declivity	1	Even, of flush with the surface
		2	Forming ridges and furrows
		3	Bearing teeth around the declivity
23.	First interstriae	1	Parallel (sometimes slightly broadened towards elytral summit)
		2	Distinctly broadened towards the summit of elytral disc
		3	Parallel on disc but broadened towards the apex of the elytra, where it sometimes bear tubercles
24.	Body Color (BC)	1	Uniformly light brown (pronotum sometimes seems lighter)
		2	Uniformly reddish (pronotum sometimes seem lighter)
		3	Uniformly dark brown (pronotum sometimes seems lighter)
		4	Uniformly black (pronotum sometimes slightly lighter)
		5	Pronotum much lighter (yellow or orange) than darker elytra

Source: Adapted from Hulcr & Smith (2010); Smith et al. (2022), online sources

Table 3-4:
List of quantitative and qualitative morphological traits used for Platypodinae morphometric analysis.

No.	Characters	Type	Description
<u>Quantitative</u>			
1.	Body Length (BL)	BL	Measured in millimeters (mm)
<u>Qualitative</u>			
2.	Frontal Carina (FC)	1	Absent
		2	Present
3.	Frons Setae (FS)	1	Setae slender, filamentous, not visibly broadened at base
		2	Setae robust, visibly thickened or stout under magnification
4.	Pronotum carina (PC)	1	Absent
		2	Present
5.	Pronotum Shape (PS)	1	Constricted
		2	Quadrilateral
6.	Surface Sculpture (SS)	1	Densely punctuated
		2	Sparse punctuated
7.	Elytra striae (ES)	1	Uniserate rows
		2	Sparse
8.	Elytra apical setae (EAS)	1	Densely covered
		2	Sparse/confused
9.	Elytra apical spine (EASP)	1	Absent
		2	Present
10.	Elytra tubercles (ET)	1	Absent
		2	Present
11.	Elytral Declivity (ED)	1	Rounded
		2	Truncated
		3	Furrows and ridges
		4	Attenuated
		5	Keeled declivity

Source: Adapted from Bickerstaff et al. (2019), online sources

3.4 Statistical Analysis

3.4.1 Diversity Analysis

The analysis was conducted using PAST software Version 4.03 (Hammer et al., 2001), a robust tool for ecological data analysis. The prepared dataset was imported into PAST via the File > Import Data menu, ensuring that columns represented species while rows denoted sample sites. This ensured the dataset was formatted correctly for subsequent calculations.

The diversity of ambrosia beetles was assessed using several indices (Table 3-5), including the Shannon–Wiener diversity index (H'), Species Evenness index (E), and Simpson’s dominance index (C) (Tarno et al., 2016). A total of 141 samples of Scolytinae and 29 samples of Platypodinae collected from eight plots across LPF42 and Sabal FR were included in the analysis. The Shannon–Wiener index (H') was applied to measure species diversity by incorporating both species richness and evenness, while the evenness index (E) was calculated to indicate the uniformity of individual distribution among species. Simpson’s dominance index (C) was also computed to evaluate the extent to which a single or a few species dominated the community. The indices were calculated separately for each site to enable comparative analysis of ambrosia beetle diversity across different habitats.

Table 3-5:
Value and description of the index for the diversity indices

Indices	Index Value	Description
Shannon-weiner (H)	<1	Low level of diversity, low individual distribution of each species
	1-3	Middle level of diversity, middle level of individual distribution for each species
	>3	High level of diversity, high level of individual distribution for each species
Simpson Dominance (C)	$0.00 < C < 0.50$	Low dominance of species
	$0.50 < C < 0.75$	Middle dominance of species
	$0.75 < C < 1$	High dominance of specie
Species Evenness	$0.00 < E < 0.50$	Evenness is low, Community is under pressure
	$0.50 < E < 0.75$	Evenness is medium level, Community is unstable
	$0.75 < E < 1.00$	Evenness is high, Community is stable

Source: (Tarno et al. 2016)

3.4.2 Morphological Analysis

3.4.2.1 Data Selection and Trait Measurement

As for data selection, only species represented by more than three individuals were included in the analysis to ensure sufficient replication and minimise bias from under-sampled taxa (Ospina-Garcés et al., 2021). Two categories of traits were considered: Quantitative and qualitative traits.

Quantitative traits – for Scolytinae, five (5) continuous variables: body length (BL), pronotum length (PL), pronotum width (PW), elytra length (EL), and elytra width (EW). These dimensions have long been recognised as diagnostic in scolytine taxonomy (Rabaglia et al., 2006). For Platypodinae, only body length (BL) was recorded as a general size reference, consistent with available taxonomic keys. Measurements were taken under a stereomicroscope using calibrated imaging software and repeated twice to minimise error.

Qualitative traits – for Scolytinae, 19 categorical characters such as antennal club type, pronotum slope, pronotum tessellation, elytral declivity contour, vestiture, and procoxae concavity, based on established taxonomic keys (Hulcr & Cognato, 2013; Wood, 2007). For Platypodinae, ten (10) qualitative characters were examined, focusing on diagnostic structural features such as frontal carina, pronotal carina, elytral declivity form, and apical spination. These trait sets differ due to morphological divergence between the two subfamilies. Only variable traits were retained for analysis, while invariant characters were excluded. Trait states were coded into a binary matrix for analysis.

3.4.2.2 Descriptive Statistics

For each quantitative trait, summary descriptive statistics (mean, standard deviation [SD], minimum, and maximum values) were calculated per species. These descriptive measures provided an initial overview of the central tendency and range of variation for each trait before inferential analyses were conducted. Similarly, for qualitative traits, frequency distributions (%) were generated to visualise the occurrence of each trait state across species.

3.4.2.3 Univariate Analysis

Normality of the quantitative dataset was assessed using Shapiro–Wilk in PAST v4.12 (Hammer et al., 2001). As the traits deviated significantly from normal distributions, non-parametric methods were applied. For quantitative traits, interspecific differences were tested using the Kruskal–Wallis test. For qualitative traits, Chi-square tests were applied to

evaluate whether observed trait frequencies deviated significantly among species.

3.4.2.4 Multivariate Analysis

To examine overall patterns and species-level clustering, both quantitative and qualitative traits were subjected to multivariate analyses:

Quantitative traits: Principal Component Analysis (PCA) was used to summarize variance and identify traits contributing most to species differences (Landi et al., 2017). PERMANOVA based on Euclidean distances tested the statistical significance of group differences, and SIMPER analysis quantified the relative contribution of each trait to interspecific dissimilarity (Clarke, 1993).

Qualitative traits: Principal Coordinates Analysis (PCoA) was performed on the binary dataset using Jaccard distances to visualize clustering patterns. PERMANOVA tested the significance of observed separations, while SIMPER identified the most important qualitative traits contributing to dissimilarity.

CHAPTER 4:

FINDINGS AND DISCUSSION

4.1 Introduction

The study examined the diversity and morphological variation of ambrosia beetles in Western Sarawak, focusing on species richness, distribution patterns, and morphological traits from exotic forest plantations at two contrasting sites. Section 4-2 highlights species composition and diversity indices, showing the dominance of *Xylosandrus crassiusculus* within Scolytinae, while Platypodinae species occurred in much lower numbers and were site-specific. Differences in diversity indices between LPF42 and Sabal FR suggest that plantation type and site conditions shape beetle community structure. Section 4-3 explores morphological variation using both qualitative and quantitative traits. Singletons were excluded from the analysis, and comparisons were focused on *X. crassiusculus*, *X. ferrugineus*, *X. artestriatus* and *X. affinis*. Results showed clear interspecific differentiation within Scolytinae, while *X. crassiusculus* displayed relatively consistent morphology across sites.

4.2 Findings

4.2.1 Diversity of Ambrosia beetles

4.2.1.1 Species Composition

A summary of species composition, their abundance, and distribution across the study sites is presented in Table 4-1. A total of 14 species (11 species of Scolytinae and three species of Platypodinae) of ambrosia beetles were recorded from the two study sites, with variations observed between LPF42 and Sabal FR. The beetles identified belonged to the subfamilies Scolytinae and Platypodinae, with Scolytinae being

the most dominant, comprising 161 individuals, while Platypodinae accounted for 9 individuals.

Table 4-1:
The total number of Ambrosia beetles collected in the intercept panel traps baited with ethanol in exotic forest plantations from two study sites in western Sarawak.

Subfamily	Species	LPF 42	Sabal FR	Total no. of beetles (N)	(% of N)	No. of Species
Scolytinae	<i>Xylosandrus crassiusculus</i>	115	26	141	82.94	11 species
	<i>Dryocoetes himalayensis</i>	2	0	2	1.18	
	<i>Xyleborus affinis</i>	1	3	4	2.35	
	<i>Xyleborus artestriatus</i>	0	3	3	1.76	
	<i>Eccoptyterus spinosus</i>	0	1	1	0.59	
	<i>Coccotrypes</i> sp.	0	2	2	1.18	
	<i>Xyleborus perforans</i>	0	1	1	0.59	
	<i>Xyleborus ferrugineus</i>	2	1	3	1.76	
	<i>Arixyleborus setosus</i>	0	1	1	0.59	
	Scolytinae sp.	0	1	1	0.59	
	<i>Xyleborus pfeillii</i>	1	1	2	1.18	
Platypodinae	<i>Dinoplatypus pseudocupulatus</i>	7	0	7	4.12	3 species
	Platypodinae sp.	0	1	1	0.59	
	<i>Euplatypus paralellus</i>	1	0	1	0.59	
	TOTAL	129	41	170	100	14 species

Table 4-1 summarises the species composition and abundance of ambrosia beetles collected from LPF42 and Sabal FR. A total of 170 individuals representing 14 taxa were recorded across both study sites, with LPF42 contributing 129 individuals and Sabal FR contributing 41 individuals.

Scolytinae overwhelmingly dominated the assemblage, accounting for the majority of both species and individuals. Of the total captures, 11 species comprising 161 individuals belonged to Scolytinae, whereas only three species comprising nine individuals were recorded under Platypodinae. This indicates a pronounced imbalance in subfamily representation within the sampled habitats.

Xylosandrus crassiusculus (Figure 4-1a & Figure 4-1b) was the most abundant species overall, comprising 82.94% of total captures. Although present at both sites, its abundance was markedly higher at LPF42 (115 individuals) compared to Sabal FR (26 individuals). This dominance resulted in a highly uneven species distribution across both locations.

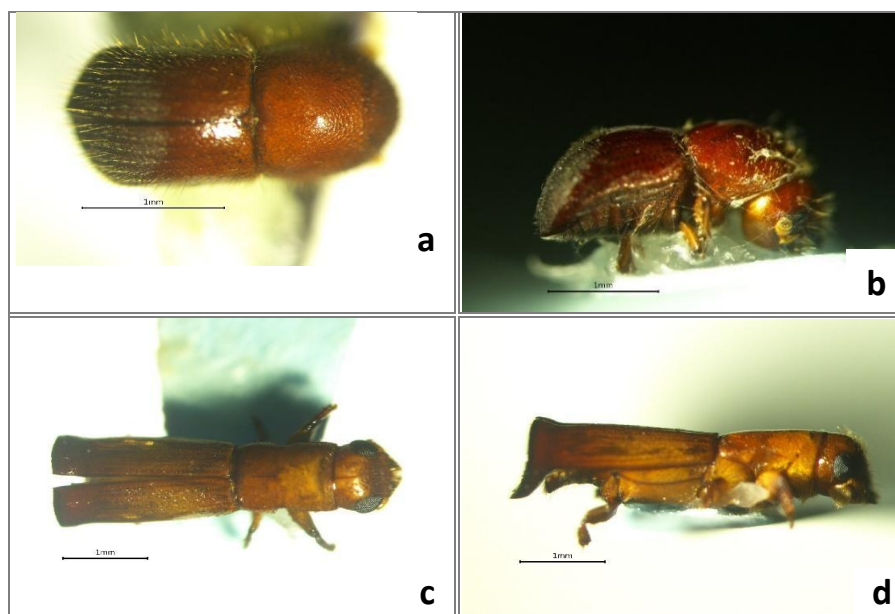
In contrast, the remaining scolytine species were represented by low individual counts, each contributing less than 3% of the total assemblage. Several species exhibited site-specific occurrences. For instance, *Dryocoetes himalayensis* was recorded exclusively at LPF42, while *Xyleborus artestriatus*, *Eccoptopterus spinosus*, *Coccotrypes* sp., *Xyleborus perforans*, *Arixyleborus setosus*, and Scolytinae sp. were recorded only at Sabal FR. This suggests subtle differences in species composition between the two plantation systems despite the shared dominance of *X. crassiusculus*.

Within Platypodinae, *Dinoplatypus pseudocupulatus* was the most prevalent species, contributing 4.12% of the total individuals and occurring exclusively at LPF42. The remaining platypodine taxa, *Euplatypus paralellus* and Platypodinae sp., were each represented by a single individual, indicating low abundance and limited distribution.

Overall, the assemblage structure across both sites was characterised by high numerical dominance of a single species and low relative abundance of multiple rare taxa, resulting in reduced evenness within the community.

Although LPF42 recorded a higher overall abundance, Sabal FR exhibited a comparable number of low-frequency taxa relative to total individuals collected, indicating potential differences in species distribution patterns between sites.

Figure 4-1:
Images of the dominant species recorded for subfamily Scolytinae and Platypodinae



Note: Scolytinae (a & b) and Platypodinae (c & d) captured using internal digital camera installed on the stereo microscope; a) Dorsal view of *X. crassiusculus*, magnification of 2×; b) Lateral view of *X. crassiusculus*, magnification of 1.5×; c) Dorsal view of *D. pseudocupulatus*, magnification of 1.2×; and d) Lateral view of *D. pseudocupulatus*, magnification of 1.2×.

4.2.1.2 Diversity Indices

The diversity of ambrosia beetles was assessed using the Shannon-Wiener Index (H'), Species Evenness Index (E), and Simpson's Dominance Index (C). These indices provide insights into species richness, distribution uniformity, and dominance across different plantation types.

The results indicate distinct differences between LPF42 and Sabal FR (Table 4-2). LPF42 recorded a low Shannon-Wiener diversity index of 0.50, suggesting low species richness. Conversely, Sabal FR exhibited a moderate diversity level with an index of 1.45, reflecting a greater variety of species. Tarno et al. (2016) classified diversity levels as low (<1), intermediate (1–3), and high (>3), placing LPF42 in the low diversity category and Sabal FR in the intermediate range.

Table 4-2:
Species diversity indices in two study sites in western Sarawak.

Study Site	Shannon-Wiener (H)	Evenness (e ^{H/S})	Simpson (1-D)	Species Richness
LPF42	0.50 (Low)	0.24 (Low)	0.20 (Low)	7
Sabal FR	1.45 (Middle)	0.39 (Low)	0.58 (Middle)	11

*Licenced Planted Forest (LPF), Sabal Forest Reserve (Sabal FR)

Similarly, the evenness index was higher in Sabal FR (0.39) than in LPF42 (0.24), indicating a slightly more balanced species distribution in the former. Low evenness in LPF42 suggests that certain species, particularly *X. crassiusculus*, dominated the community. The Simpson's Dominance Index further supports this observation, with LPF42 recording a low value (0.20), indicating a high dominance of a single species, whereas Sabal FR had a moderate value of 0.58, reflecting a more diverse and evenly distributed community.

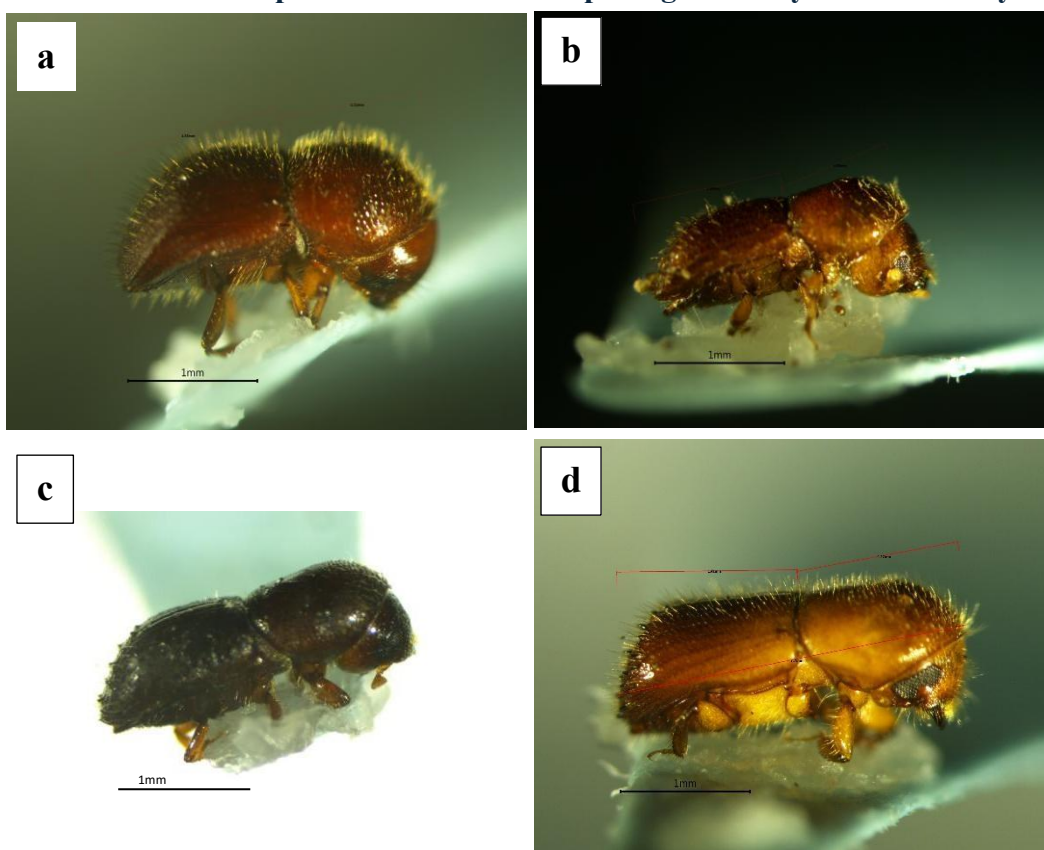
4.2.2 Morphological Variation

Based on the data presented in Table 4-1, only species represented by more than three individuals were included for morphological analysis, as outlined in the methodology. Accordingly, four species were selected (Figure 4-2): *Xylosandrus crassiusculus* (141 individuals), *Xyleborus affinis* (4 individuals), *Xyleborus artestriatus* (3 individuals), and *Xyleborus ferrugineus* (3 individuals). These species provided sufficient replication to ensure meaningful comparisons, while minimising potential bias from under-sampled taxa.

Although *Dinoplatypus pseudocupulatus* (Platypodinae) was represented by more than three individuals (n = 7), multivariate interspecific analysis was not conducted for Platypodinae. This is because only one platypodine species met the replication threshold, and multivariate ordination and group comparison methods require at least two species-level groups for meaningful discrimination. The remaining Platypodinae taxa were represented by single individuals, rendering comparative morphometric analysis within this subfamily statistically inappropriate.

Furthermore, intraspecific variation within Platypodinae was not analysed separately because *D. pseudocupulatus* was recorded from only one study site (LPF42). In the absence of spatial or ecological grouping variables, statistical comparison of within-species variation would not yield biologically interpretable patterns. Consequently, morphological analyses focused on Scolytinae species represented across both study sites, allowing robust inter- and intraspecific comparisons.

Figure 4-2:
Ambrosia beetle species selected for morphological analysis in this study



Note: (a) *Xylosandrus crassiusculus* (141 individuals), (b) *Xyleborus affinis* (4 individuals), (c) *Xyleborus artestriatus* (3 individuals), and (d) *Xyleborus ferrugineus* (3 individuals). Scale bars = 1 mm.

4.2.2.1 Quantitative Characters

Descriptive statistics of five quantitative morphological characters are presented in Table 4-3. Across the four species, significant differences were observed for all traits (Kruskal–Wallis, $p < 0.001$). *Xylosandrus ferrugineus* was consistently the largest species, exhibiting the greatest body length (2.76–2.77 mm), pronotum length (1.33–1.35 mm), and elytra length (1.60–1.64 mm). *Xylosandrus crassiusculus* was slightly smaller but showed similar pronotum and elytra dimensions to *X. ferrugineus*. In contrast, *X. affinis* was the smallest species, with the shortest body (2.06–2.67 mm), pronotum (1.04–1.08 mm), and the narrowest pronotum (0.53–0.61 mm) and elytra (0.38–0.40 mm). *Xyleborus artestriatus* occupied an intermediate position but was distinguished by relatively short elytra (1.37–1.38 mm) and the widest elytra (0.48–0.50 mm). These results demonstrate strong interspecific separation based on quantitative morphology.

Table 4-3:
Descriptive statistics of quantitative morphological characters of ambrosia beetle species and Kruskal–Wallis test results.

Character	Species	Mean	SD	Min	Max	H	P
BL	<i>X. crassiusculus</i>	2.55	0.08	2.42	2.67	16.5	<0.001
	<i>X. affinis</i>	2.22	0.30	2.06	2.67		
	<i>X. artestriatus</i>	2.41	0.11	2.34	2.57		
	<i>X. ferrugineus</i>	2.76	0.01	2.76	2.77		
PL	<i>X. crassiusculus</i>	1.33	0.01	1.31	1.35	25.07	<0.001
	<i>X. affinis</i>	1.06	0.02	1.04	1.08		
	<i>X. artestriatus</i>	1.10	0.02	1.07	1.11		
	<i>X. ferrugineus</i>	1.34	0.01	1.33	1.35		
PW	<i>X. crassiusculus</i>	1.06	0.01	1.04	1.08	23.71	<0.001
	<i>X. affinis</i>	0.57	0.04	0.53	0.61		
	<i>X. artestriatus</i>	0.88	0.01	0.87	0.89		
	<i>X. ferrugineus</i>	1.06	0.02	1.05	1.08		
EL	<i>X. crassiusculus</i>	1.62	0.01	1.60	1.65	24.66	<0.001
	<i>X. affinis</i>	1.45	0.04	1.40	1.50		
	<i>X. artestriatus</i>	1.38	0.01	1.37	1.38		
	<i>X. ferrugineus</i>	1.62	0.02	1.60	1.64		
EW	<i>X. crassiusculus</i>	0.47	0.01	0.44	0.48	24.15	<0.001
	<i>X. affinis</i>	0.39	0.01	0.38	0.40		
	<i>X. artestriatus</i>	0.49	0.01	0.48	0.50		
	<i>X. ferrugineus</i>	0.47	0.01	0.47	0.48		

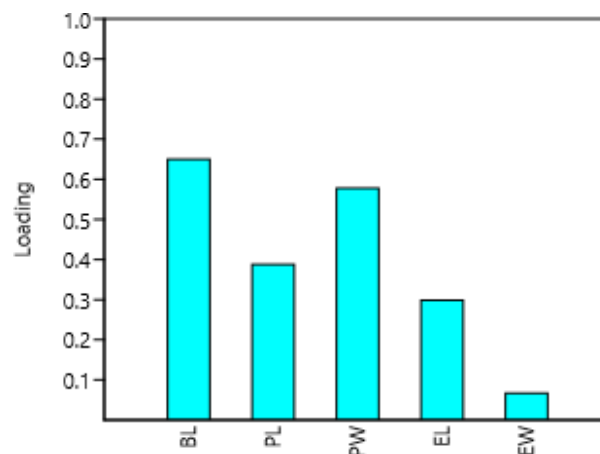
Note: Body length (BL), Pronotum length (PL), Pronotum width (PW), Elytra length (EL), and Elytral width (EW). SD = standard deviation (a measure of variation around the mean); Min = minimum value; Max = maximum value; H = Kruskal–Wallis test statistic; p = probability value indicating the significance of differences among species.

While descriptive statistics highlight the range and central tendency of individual traits across species, a multivariate approach such as Principal Component Analysis (PCA) provides deeper insight by summarising overall variation patterns and identifying which traits most strongly contribute to interspecific differences. PCA was performed on five quantitative morphological traits of four Ambrosia beetle species (*X. crassiusculus*, *X. affinis*, *X. artestriatus*, and *X. ferrugineus*). The first two components explained 95.47% of the total variation, with PC1 accounting for 81.67% and PC2 for 13.80% of the variance (Table 4-4). PCA loadings indicated that body length (0.68) and pronotum width (0.58) contributed most strongly to PC1, followed by pronotum length (0.42) and elytra length (0.30), while elytra width (0.08) contributed minimally (Figure 4-3).

Table 4-4:
Summary of Principal Component Analysis (PCA) for five quantitative morphological characters across four species (*X. crassiusculus*, *X. affinis*, *X. artestriatus* and *X. ferrugineus*).

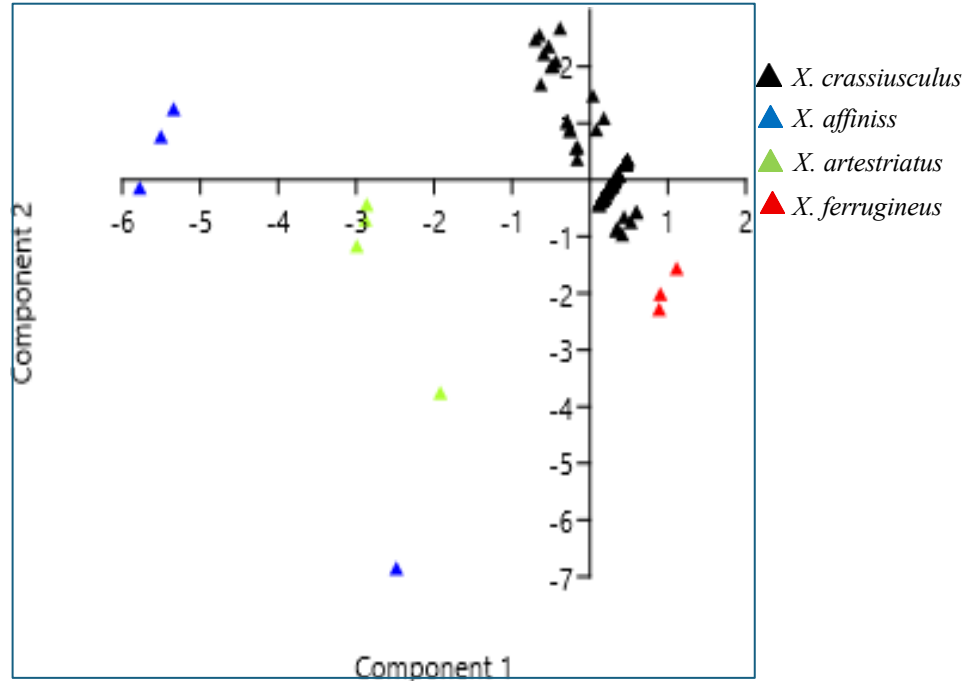
PC	Eigenvalue	% Variance Explained	Cumulative %
1	0.0193227	81.67%	81.67%
2	0.00326375	13.80%	95.47%
3	0.000930944	3.93%	99.40%
4	0.00011825	0.50%	99.90%
5	2.36E-05	0.10%	100%

Figure 4-3:
Principal Components Analysis (PCA) loadings for five quantitative morphological traits of *X. crassiusculus*, *X. affinis*, *X. artestriatus*, and *X. ferrugineus*.



The scatter plot of PCA (Figure 4-4) showed distinct clustering of species. *X. ferrugineus* was separated on the positive axis of PC1, while *X. affinis* and *X. artestriatus* were positioned on the negative axis. *Xylosandrus crassiusculus* formed a compact cluster closer to the center-right. Along PC2, *X. affinis* and *X. artestriatus* were more dispersed, suggesting greater intraspecific variation compared to the tightly grouped *X. crassiusculus* and *X. ferrugineus*. These results indicate that body length and pronotum dimensions are the primary traits driving species separation among the four species of ambrosia beetle.

Figure 4-4:
Principal Components Analysis (PCA) plot of *X. crassiusculus*, *X. affinis*, *X. artestriatus*, and *X. ferrugineus*.



A Permutational Multivariate Analysis of Variance (PERMANOVA) test based on Euclidean distances of quantitative traits showed significant morphological differentiation among the four ambrosia beetle species ($F = 15.83$, $p = 0.0001$). This indicates that interspecific variation is much greater than intraspecific variation, confirming the distinctiveness of species-level morphological traits.

The multivariate analyses (PCA and PERMANOVA) revealed significant differences among species based on quantitative morphological traits. To further identify which characters contributed most to these differences, a SIMPER analysis was performed (Table 4-5). The results showed that body length (BL) and pronotum width (PW) were the two most important contributors, accounting for 37.07% and 34.90% of dissimilarity, respectively. Together with pronotum length (PL, 15.77%) and elytra length (EL, 11.40%), these four traits explained over 99% of the variation among species, while elytra width (EW) had only a minor influence (0.86%).

These results align closely with the PCA loadings, where BL and PW exhibited high values along the first principal component, which explained 81.67% of the variance. The strong agreement between SIMPER and PCA emphasises that body size and pronotum proportions are the primary morphological traits distinguishing the four ambrosia beetle species.

Table 4-5:
Contribution of quantitative morphological traits to interspecific dissimilarity among four ambrosia beetle species based on SIMPER analysis.

Taxon	Av. Dissim	Contrib. %	Cumulative %	Mean Sp. 1	Mean Sp. 2	Mean Sp. 3	Mean Sp.4
BL	0.1076	37.07	37.07	2.6	2.22	2.4	2.76
PW	0.1013	34.9	71.97	1.06	0.57	0.878	1.06
PL	0.04579	15.77	87.75	1.33	1.06	1.1	1.34
EL	0.03309	11.4	99.14	1.62	1.45	1.38	1.62
EW	0.002489	0.8573	100	0.468	0.392	0.49	0.473

Note: Body length (BL), Pronotum length (PL), Pronotum width (PW), Elytra length (EL), Elytra width (EW), Sp.1: *X. crassiusculus*, Sp.2: *X. affinis*, Sp. 3: *X. artestriatus*, and Sp. 4: *X. ferrugineus*

4.2.2.2 Qualitative Characters

A total of 19 qualitative morphological traits were examined across four species. The frequency distribution of these traits is presented in Table 4-6. Most characters were uniform within species, with fixed states expressed in 100% of the individuals. For example, all specimens of *X. crassiusculus* exhibited club type 1 and pronotum slope type 1, while *X. affinis* consistently expressed club type 1 but pronotum slope type 2. Similar fixed patterns were also observed for *X. artestriatus* and *X. ferrugineus*. The lack of intraspecific variability and the strong interspecific differences resulted in highly significant Chi-square values ($p < 0.001$) for most traits. No variation was detected between sites (LPF42 and Sabal FR) for *X. crassiusculus*, as the same character states were observed in all individuals regardless of location.

Table 4-6:
Frequency distribution (%) of qualitative morphological traits of ambrosia beetle
species across four species (A) and *X. crassiusculus* across two study sites (B).

Traits	Type	(A)				(B)		
		Sp. 1 (n=141)	Sp. 2 (n=4)	Sp. 3 (n=4)	Sp.4 (n=3)	Chi Square	LPF42	SFR
FT	1	0.00	0.00	0.00	0.00	0		
	2	100	100	100	100		100	100
CS	1	100	100	0	100	152***	100	100
	7	0	0.00	100	0			
PSL	1	100	0.00	0.00	100	304***	100	100
	2	0	100	0.00	0.00			
	3	0.00	0.00	0.00	0.00			
	4	0.00	0.00	0.00	0.00			
	5	0.00	0.00	0.00	0.00			
	6	0.00	0.00	0.00	0.00			
	7	0.00	0	100	0			
PSD	1	0.00	0.00	0.00	0.00	152***		
	2	100	100	0.00	100		100	1001
	3	0.00	0.00	0.00	0.00			
	4	0.00	0.00	0.00	0.00			
	5	0.00	0.00	0.00	0.00			
	6	0.00	0.00	0.00	0.00			
	7	0.00	0.00	100	0.00			
	8	0.00	0.00	0.00	0.00			
PCC	1	0.00	100	100	0.00	152***		
	2	100	0.00	0.00	100		100	100
PTES	1	0.00	0.00	0.00	0.00	152***		
	2	0.00	100	100	100			
	3	0.00	0.00	0.00	0.00			
	4	100	0.00	0.00	0.00		100	100
PTPE	1	0.00	0.00	100	100	152***		
	2	100	100	0.00	0.00		100	100
PTSD	1	100	100	100	100	0	100	100
	2	0.00	0.00	0.00	0.00			
	3	0.00	0.00	0.00	0.00			
EBS	1	100	100	100	100	0	100	100
	2	0.00	0.00	0.00	0.00			
SC	1	100	100	0.00	100		100	100
	2	0.00	0.00	100	0.00			
	3	0.00	0.00	0.00	0.00			
EDC	1	0.00	100	100	100	152***		
	2	100	0.00	0.00	0.00		100	100
	3	0.00	0.00	0.00	0.00			
	4	0.00	0.00	0.00	0.00			
EDP	1	100	100	100	100	0	100	100
	2	0.00	0.00	0.00	0.00			
EDSL	1	100	0.00	0.00	0.00	152***	100	1001
	2	0.00	100	100	100			
	3	0.00	0.00	0.00	0.00			
	4	0.00	0.00	0.00	0.00			
	5	0.00	0.00	0.00	0.00			
	6	0.00	0.00	0.00	0.00			
	7	0.00	0.00	0.00	0.00			
	8	0.00	0.00	0.00	0.00			

Table 4-6: Continued.

Traits	Type	(A)				(B)		
		Sp. 1 (n=141)	Sp. 2 (n=4)	Sp. 3 (n=4)	Sp.4 (n=3)	Chi Square	LPF42	SFR
EDSD	1	100	100	100	100	0	100	100
	2	0.00	0.00	0.00	0.00			
	3	0.00	0.00	0.00	0.00			
	4	0.00	0.00	0.00	0.00			
	5	0.00	0.00	0.00	0.00			
	6	0.00	0.00	0.00	0.00			
EDV	1	100	0.00	0.00	0.00	152***	100	100
	2	0.00	100	100	100			
	3	0.00	0.00	0.00	0.00			
	4	0.00	0.00	0.00	0.00			
TP	1	100	100	0.00	0.00	304***	100	100
	2	0.00	0.00	100	0.00			
	3	0.00	0.00	0.00	100			
	4	0.00	0.00	0.00	0.00			
	5	0.00	0.00	0.00	0.00			
	6	0.00	0.00	0.00	0.00			
	7	0.00	0.00	0.00	0.00			
UDS	1	100	100	100	100	0	100	100
	2	0.00	0.00	0.00	0.00			
	3	0.00	0.00	0.00	0.00			
IS1	1	100	100	0.00	0.00	152***	100	100
	2	0.00	0.00	0.00	0.00			
	3	0.00	0.00	100	100			
BC	1	100	100	0.00	100	152***	100	100
	2	0.00	0.00	100	0.00			
	3	0.00	0.00	0.00	0.00			
	4	0.00	0.00	0.00	0.00			
	5	0.00	0.00	0.00	0.00			

Note: Frons texture (FT), Club shape (CS), Pronotum shape in lateral view (PSL), Pronotum Shape in dorsal view (PSD), Procoxae condition (PCC), Protibiae edge shape (PTES), Protibia posterior edge (PTPE), No. of protibia socketed denticles (PTSD), Scutellum (SC), Shape of elytral base (EBS), Elytral disc convexity (EDC), Punctures on elytral disc (EDP), Shape of elytral declivity (EDSL), Shape of elytral declivity (EDSD), Vestiture on elytral declivity (EDV), Tubercle pattern (TP), Striae or interstriae on the upper part of the declivity (UDS), First interstriae (IS1), Body color (BC). Sp.1: *X. crassiusculus*, Sp.2: *X. affinis*, Sp. 3: *X. artestriatus*, and Sp. 4: *X. ferrugineus*

To highlight the diagnostic importance of these traits, Table 4-7 summarises which traits were found to be species-specific (diagnostic) versus non-diagnostic. Traits such as pronotum shape in lateral view (PSL), pronotum shape in dorsal view (PSD), and elytra declivity convexity (EDC) were strongly diagnostic. In contrast, six traits, including frons texture (FT) and striae or interstriae on the upper part of the declivity (UDS), were invariant across species.

Table 4-7:
Diagnostic and non-diagnostic qualitative traits of ambrosia beetle species with Chi-square test results

Trait Code	Trait Description	Diagnostic Value	Chi-square (χ^2)	Interpretation
CS	Club Shape	Diagnostic	152***	Species-specific
PSL	Pronotum Shape in Lateral View	Diagnostic	304***	Strong separation
PSD	Pronotum Shape in Dorsal View	Diagnostic	152***	Diagnostic for <i>X. artestriatus</i>
PCC	Pronotum Central Carina	Diagnostic	152***	Species-specific
PTES	Pronotum Texture	Diagnostic	152***	Species-specific
PTPE	Protibiae Posterior Edge	Diagnostic	152***	Species-specific
SC	Scutellum	Diagnostic	152***	Distinguishes species
EDC	Elytra Declivity Convexity	Diagnostic	152***	Strong separation
EDSL	Elytra Disc Shape in Lateral View	Diagnostic	152***	Species-specific
EDV	Elytra Declivity Vestiture	Diagnostic	152***	Species-specific
TP	Tubercle Pattern	Diagnostic	304***	Strong separation
IS1	Interstriae 1	Diagnostic	152***	Species-specific
BC	Body Color	Diagnostic	152***	Species-specific
FT	Frons Texture	Non-diagnostic	0	Same in all species
PTSD	Pronotum Shape (dorsal)	Non-diagnostic	0	Invariant across species
EBS	Elytra Base Shape	Non-diagnostic	0	Invariant across species
EDP	Elytra Disc Puncture	Non-diagnostic	0	Invariant across species
EDSD	Elytra Declivity Shape (Dorsal)	Non-diagnostic	0	Invariant across species
UDS	Striae or interstriae on the upper part of declivity	Non-diagnostic	0	Invariant across species

Note: *** indicated p value <0.0001

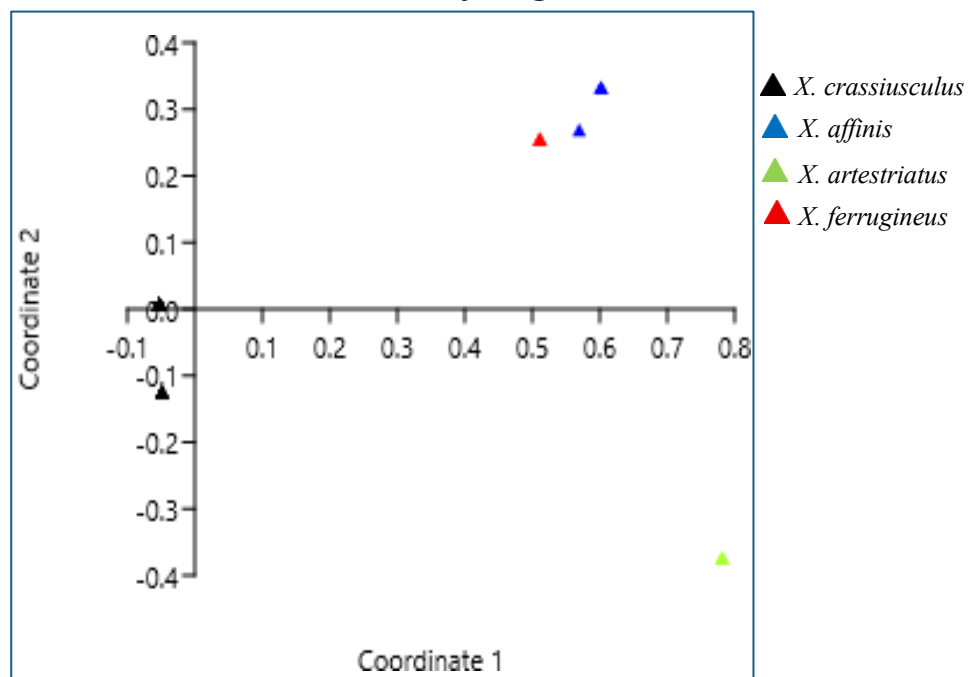
As summarised in the preceding table, a subset of qualitative traits was identified as diagnostic characters distinguishing the four ambrosia beetle species, while the remaining traits were considered non-diagnostic and excluded from further multivariate analysis. The eigenvalue summary (Table 4-8) shows that the first two coordinates captured 91.6% of the total variance among the diagnostic traits, with Coordinate 1 (PCoA1) explaining 72.3% and Coordinate 2 (PCoA2) accounting for 19.3%. Subsequent coordinates contributed minimally (<8% combined). Accordingly, species separation was primarily visualized along the first

two axes in the PCoA scatter plot (Figure 4-5). *Xylosandrus crassiusculus* clustered tightly near the origin, reflecting low intraspecific variation in diagnostic morphology. In contrast, *X. affinis*, *X. artestriatus*, and *X. ferrugineus* formed distinct but separate clusters, indicating species-specific diagnostic features. The separation observed in PCoA reflects the significant differences detected in traits such as club shape, pronotal slope, and elytral declivity (χ^2 tests, $p < 0.001$). These traits are therefore likely to contribute most strongly to the observed species separation.

Table 4-8:
Summary of Principal Coordinates Analysis (PCoA) based on Jaccard distances of diagnostic qualitative traits for four ambrosia beetle species.

Axis	Eigenvalue	Percent of Variance (%)	Cumulative (%)
1	5.0026	72.26	72.26
2	1.3375	19.32	91.58
3	0.5264	7.6	99.18
4	0.0433	0.63	99.81
5–29	<0.000001	<0.001 each	100

Figure 4-5:
Principal Coordinates of Analysis (PCoA) plot of *X. crassiusculus*, *X. affinis*, *X. artestriatus*, and *X. ferrugineus*.



To statistically validate these observed patterns, a PERMANOVA based on Jaccard distances was conducted. The results revealed a highly significant difference in qualitative morphological traits among the four ambrosia beetle species ($F = 1507$, $p = 0.0001$). The very high F-value indicates that variation is strongly structured by species identity, with between-species differences far exceeding within-species variation. This finding corroborates the distinct clustering observed in the PCoA scatter plot, confirming the diagnostic power of qualitative traits for species delimitation.

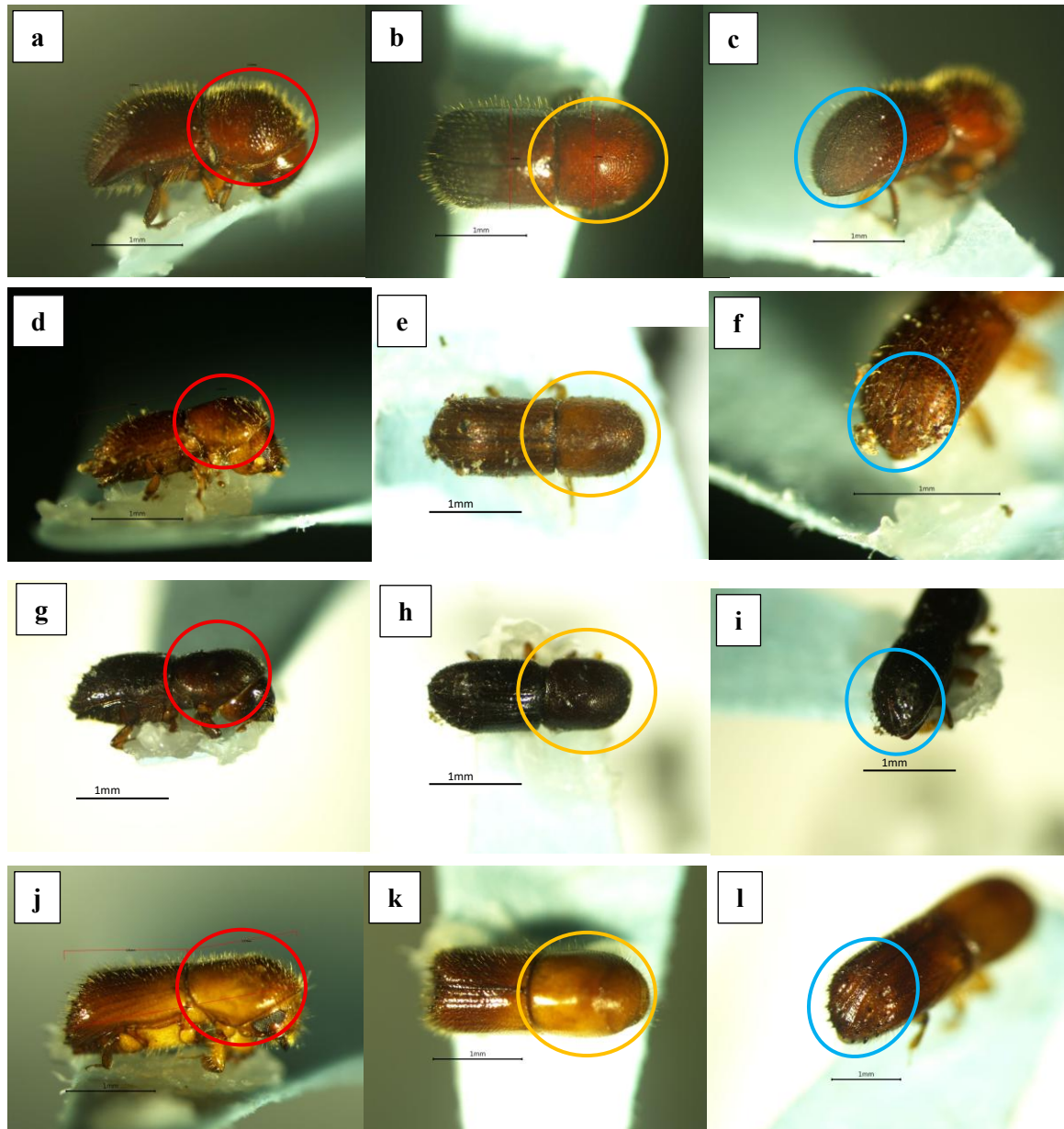
SIMPER analysis (Table 4-9) revealed that qualitative traits related to the elytral declivity (EDV, EDC, EDSL) and protibiae edge shape (PTES) were the most important contributors to interspecific dissimilarity, each explaining ~5.5% of variation. Collectively, these characters accounted for ~45% of the dissimilarity. Additional contributors included procoxae condition (PCC), further increasing the cumulative variation explained to over 50%. These findings are consistent with the PCoA ordination, where species separation was primarily structured by variation in elytral declivity and pronotal morphology, underscoring their taxonomic importance in distinguishing closely related Ambrosia beetle species.

Table 4-9:
SIMPER results showing the top 10 qualitative traits contributing to dissimilarity among *Xylosandrus crassiusculus*, *Xyleborus affinis*, *X. artestriatus*, and *X. ferrugineus* based on Bray–Curtis dissimilarities.

Rank	Trait	Av. dissim	Contrib. %	Cumulative %	Mean Sp. 1	Mean Sp. 2	Mean Sp. 3	Mean Sp. 4
1	EDV1	3.72	5.53	5.53	1	0	0	0
2	EDC1	3.72	5.53	11.06	0	1	1	1
3	EDSL2	3.72	5.53	16.6	0	1	1	1
4	PTES4	3.72	5.53	22.13	1	0	0	0
5	EDC2	3.72	5.53	27.66	1	0	0	0
6	EDSL1	3.72	5.53	33.19	1	0	0	0
7	EDV2	3.72	5.53	38.73	0	1	1	1
8	PTES2	3.72	5.53	44.26	0	1	1	1
9	PCC2	2.76	4.1	48.36	1	0	0	1
10	PCC1	2.76	4.1	52.46	0	1	1	0

Note: Elytral declivity vestiture type 1 (EDV1), Elytral declivity convexity type 1 (EDC1), Elytral declivity shape in lateral view type 2 (EDSL2), Protibiae edge shape type 4 (PTES4), Elytral declivity convexity type 2 (EDC2), Elytral declivity shape in lateral view type 1 (EDSL1), Elytral declivity vestiture type 2 (EDV2), Protibiae edge shape type 2 (PTES2), Procoxae condition type 2 (PCC2), Procoxae condition type 1 (PCC1). Sp.1: *X. crassiusculus*, Sp.2: *X. affinis*, Sp.3: *X. artestriatus*, and Sp.4: *X. ferrugineus*.

Figure 4-6:
Comparative morphology of selected Scolytinae species showing diagnostic pronotal and elytral characters.



Notes: Representative images of four Scolytinae species included in the morphometric analysis: (a–c) *Xylosandrus crassiusculus*, (d–f) *Xyleborus affinis*, (g–i) *Xyleborus artestriatus*, and (j–l) *Xyleborus ferrugineus*. For each species, the lateral view illustrates the pronotal profile (red circle), the dorsal view shows the pronotal outline and overall body form (orange circle), and the close-up image highlights the elytral declivity region (blue circle). The circled areas indicate the principal diagnostic structures contributing to species separation in the multivariate morphological analyses.

4.3 Discussion

4.3.1 Beetle Diversity

The contrasting assemblages observed between LPF42 and Sabal FR reflect broader patterns reported across tropical plantations. In East Java, Tarno et al. (2022) demonstrated that protected pine forests supported significantly higher ambrosia beetle richness and abundance, while intensively managed systems recorded fewer species. This was attributed to the greater accumulation of deadwood and ecological stability in less-disturbed stands, which provide suitable habitats for beetle–fungus associations. Similarly, Setiawan et al. (2018) found that teak polyculture systems intercropped with coffee and mahogany supported slightly higher diversity ($H = 1.40$) compared to monocultures ($H = 1.30$), although both were classified as only medium diversity systems due to disturbance. These align with our findings: Sabal FR, with a mixture of indigenous and exotic species, supported a more even beetle assemblage, whereas LPF42, a monoculture embedded in oil palm, was strongly dominated by *X. crassiusculus*. Cross-biome evidence from Brazil reinforces these mechanisms. In a tropical dry forest, bark beetle richness and abundance were highest at intermediate successional stages where wood resources were abundant, while ambrosia beetles showed less response to succession but tracked microclimate and wood moisture (Macedo-Reis et al. 2016). Similarly, Cloonan et al. (2022) reported $>20\times$ higher total captures in avocado monocultures than in swamp bay forests in Florida, with very different dominant assemblages, further highlighting how monocultures under stress can amplify beetle populations.

The predominance of *X. crassiusculus* (82.94% of captures) in Sarawak reflects its widespread prevalence across Southeast Asia. In Java, it was the only species consistently present across all pine forest types (Tarno et al. 2022) and the most abundant in teak monoculture and polyculture (Setiawan et al. 2018). In a larger regional comparison across Java, Sumbawa, and Sulawesi, *X. crassiusculus* was again among the dominant taxa (27.64%), alongside *X. affinis* (47.17%) and *Hypothenemus* spp. (12.33%) (Tarno et al. 2022). Its success is attributed to its broad host range, strong ethanol responsiveness, adaptability to warm and humid climates, and continuous breeding cycles (Horn & Horn, 2006; Pennacchio et al., 2003). Similarly, in Brazilian dry forests, *X. affinis* was present at all sites and accounted for 87% of captures, underscoring its role as a disturbance-tolerant generalist with global dominance (Macedo-Reis et al., 2016). In Florida avocado orchards affected by laurel wilt, *X. crassiusculus* represented 6.5% of captures, while *X. affinis*

accounted for 1.2% (Cloonan et al., 2022). Notably, both species have been shown to act as secondary vectors of *Harringtonia lauricola*, the fungal symbiont causing laurel wilt, after acquiring it from *X. glabratus* (Cloonan et al. 2022). These results, together with Zou et al. (2011)'s resource concentration hypothesis, highlight how simplified systems repeatedly select for polyphagous, disturbance-tolerant taxa, which may also elevate biosecurity risks.

Platypodinae were less abundant but ecologically relevant. In Sarawak, *E. parallelus* and *D. pseudocupulatus* were detected at low frequencies; in Java, *E. parallelus* and *Treptoplatypus micrurus* were similarly rare (<2% of captures) (Tarno et al., 2022). Yet *E. parallelus* is known as an emerging pest in Southeast Asia, attacking *Pterocarpus indicus* and producing deep galleries inoculated with fungi (Bumrungsri et al. 2008). The Brazilian study likewise recorded *E. parallelus* as the only Platypodinae species, further demonstrating its wide distribution and persistence at low densities across biomes (Macedo-Reis et al. 2016). In Florida, Cloonan et al. (2022) also detected *E. parallelus* in both avocado and swampbay sites, albeit in low numbers, underscoring its broad adaptability. Host context also shaped beetle assemblages: in teak polyculture systems, *H. hampei* was captured more frequently where coffee was intercropped (Setiawan et al. 2018), while in Florida avocado, *Euwallacea perbrevis* (vector of *Fusarium dieback*) occurred exclusively in orchards (Cloonan et al. 2022). These findings support Zou et al. (2011) argument that neglected groups, even when rare, can have disproportionate ecological and economic impacts, justifying broad monitoring.

Environmental factors were also central. In Java pine systems, stand age ($\beta = 0.60$) and humidity ($\beta = 0.54$) increased abundance, while temperature ($\beta = -0.52$) reduced it (Tarno et al., 2022). Setiawan et al. (2018) reported species-specific flight peaks, with *X. crassiusculus* peaking earlier than *E. similis* and *X. morigerus*, suggesting environmental partitioning of activity. In Sarawak, this may partly explain why Sabal FR, with its older, more humid stands, hosted higher richness. In Brazil, Macedo-Reis et al. (2016) found that tree diameter (CBH) was the strongest predictor of beetle diversity, with bark beetle richness or abundance and *Ambrosia* abundance all increasing with CBH, confirming Grove (2002) axiom that “all wood is good, but bigger is better.” They also reported that ambrosia abundance increased with air moisture but decreased with rainfall and temperature, with richness peaking at the end of dry and wet seasons. In Florida, Cloonan et al. (2022) showed that semiochemicals strongly influenced species captures: *X. saxesenii* responded mainly to ethanol alone, *X. crassiusculus*, *X. affinis*, and *X. volvulus* responded best to cubeb + ethanol, while *X. glabratus* and *E. perbrevis* were most responsive to α -copaene lures. These patterns

confirm that beetle communities are shaped not only by stand structure and climate, but also by the volatile environment of stressed or healthy hosts, with implications for monitoring and control strategies.

At broader spatial scales, beta diversity analyses consistently show turnover as the dominant driver. Across Java, Sumbawa, and Sulawesi teak plantations, Tarno et al. (2022) reported that species replacement (β -sim = 85%) accounted for most regional β -diversity, with nestedness playing a smaller role. In Brazilian dry forests, Macedo-Reis et al. (2016) reached the same conclusion, with turnover driving 85.6% of bark beetle β -diversity and 74.4% for Ambrosia beetles. Cloonan et al. (2022) also demonstrated striking ecosystem-specific assemblages in Florida, with *X. andrewesi* and *X. glabratus* prominent in swampbay forests but nearly absent in avocado, while *X. saxesenii* and *X. crassiusculus* dominated orchards. This aligns with our observation that LPF42 and Sabal FR communities were distinct not due to simple richness differences but due to species replacement shaped by management intensity, land use, and host context. Such findings emphasise that site-level filters, stand structure, host diversity, climate, disturbance history, and host volatiles are key determinants of ambrosia beetle community composition across tropical and subtropical regions.

Taken together, these results demonstrate that ambrosia beetle diversity in Sarawak and comparable systems is structured by the interplay of biotic context (host composition, intercropping, fungal symbioses), abiotic conditions (moisture, rainfall, temperature, successional stage), and management practices (monoculture vs. polyculture, thinning, surrounding land use). From a forest management perspective, promoting mixed plantings, native buffer zones, and structural heterogeneity can reduce the dominance of disturbance-tolerant species, enhance community evenness, and improve resilience to climate variability. Equally, consistent monitoring of both dominant taxa (*X. crassiusculus*, *X. affinis*) and minor groups (*E. parallelus*, *H. hampei*, *E. perbrevis*) is necessary, as rare species may become problematic under shifting climatic, ecological, and silvicultural regimes.

4.3.2 Morphological Variation

The analyses revealed clear interspecific differentiation among the four ambrosia beetle species examined. Quantitative traits, particularly body length (BL) and pronotum width (PW), were the strongest contributors to separation in PCA and SIMPER ($\approx 37\%$ and 35% of dissimilarity, respectively). *Xyleborus ferrugineus* was consistently distinguished by its larger body size, whereas *X. affinis* and *X. artestriatus* showed comparatively smaller dimensions. These patterns align with scolytine taxonomy, where body proportions and pronotal measurements are critical diagnostic characters (Hulcr & Smith, 2010; Rabaglia et al. 2006).

Qualitative traits further reinforced these separations. PCoA clustered species into distinct, non-overlapping groups (first two axes = 91.6% of variance), and PERMANOVA ($F = 1507$, $p = 0.0001$) confirmed that these groupings were statistically robust. SIMPER highlighted elytral declivity vestiture, declivity convexity, declivity shape in lateral view, and protibial edge shape as the main contributors ($\sim 45\%$) to interspecific dissimilarity. These features are widely recognised as diagnostic in scolytine taxonomy (Wood, 2007) and are functionally significant because declivity structures influence boring mechanics and fungal inoculation (Hulcr & Stelinski, 2017).

Comparable studies affirm these diagnostic values. Valerio-Mendoza et al. (2017) demonstrated that declivital vestiture and genitalia structures reliably distinguished geographic groups of bark beetles. Thube et al. (2022) confirmed *X. crassiusculus* in India as the agent of arecanut kernel decay based on body size ($2.5\text{--}2.8$ mm), coloration, matte declivity, carinate posterolateral margins, and a pronotal mycangial tuft. Similarly, Gallego et al. (2017) identified Spanish specimens from carob (*Ceratonia siliqua*) using reddish-brown coloration, steep convex declivity, setal vestiture, and sexual dimorphism ($\text{♀ } 2.1\text{--}2.9$ mm, $\text{♂ } \sim 1.6$ mm). Such cross-regional congruence demonstrates that declivital sculpturing and pronotal traits are universally robust markers. Importantly, Hulcr and Stelinski (2017) emphasised that such morphological traits often reflect mycangial evolution, since each independent origin of ambrosia symbiosis is accompanied by new mycangial types visible in thoracic or pronotal modifications. These links reinforce that morphology and symbiosis co-evolve, explaining why certain external characters remain taxonomically stable and ecologically meaningful.

Among the species examined in this study, *X. crassiusculus* occurred in the highest abundance at both LPF42 and Sabal FR, allowing for an assessment of intraspecific variation. Minor differences in BL were observed, but clustering patterns remained consistent. Antennal club form, pronotal slope, and declivity were identical, highlighting marked morphological conservatism.

This stasis reflects global evidence. *X. crassiusculus* across Asia, Europe, and the Americas shows negligible external divergence (Rabaglia et al. 2006; Landi et al. 2017). Gallego et al. (2017) noted that European populations were morphologically indistinguishable from Asian ones despite colonising novel hosts. Thube et al. (2022) likewise found that Indian arecanut populations retained the standard suite of characters, verified by COI barcoding. Covre et al. (2021) reported that Brazilian populations spanning tropical Amazonia to subtropical Paraná maintained identical morphology despite contrasting climates and voltinism. Such findings confirm that morphological conservatism is a defining trait of *X. crassiusculus*.

Employing both metric and qualitative traits provided complementary insights. PCA captured size gradients; PCoA and PERMANOVA distinguished discrete structural clusters; and SIMPER identified which traits drove dissimilarity. This integrative approach is consistent with best practices in scolytine taxonomy, where morphology and multivariate statistics remain indispensable despite the growing use of molecular tools (Hulcr & Cognato, 2013; Vega & Hofstetter, 2015). In applied contexts, Cloonan et al. (2022) demonstrated that accurate separation of sympatric *X. affinis*, *X. crassiusculus*, and *X. volvulus* in Florida laurel wilt systems relied heavily on declivity and antennal morphology. Integrative morphometrics, therefore, not only validates taxonomic boundaries but also provides a reliable frontline for pest diagnostics.

Habitat filters such as wood size, moisture, and stand structure influence development. Larger and moister substrates can yield larger adults, while stressed or smaller hosts constrain growth (Macedo-Reis et al. 2016). These effects are often plastic, explaining why we observed only slight BL variation between LPF42 and Sabal FR. Stabilising selection is another factor. The external morphology of ambrosia beetles is largely shaped by their need to tunnel into wood and transport fungal symbionts, which restricts variation in body form. However, new ecological roles or behaviors can still arise even without noticeable changes in morphology. Thube et al. (2022) described *X. crassiusculus* exploiting

arecanut kernels (spermatophagy) without altering its external phenotype, driven instead by symbiotic flexibility with *Ambrosiella roeperi*. Similarly, Hulcr et al. (2017) showed that pest species like *X. glabratus* and *Euwallacea fornicatus* were already capable of colonising living hosts in their native ranges indicating that destructive ecology often precedes, rather than follows, invasion, without requiring morphological innovation.

Another explanation is cryptic genetic divergence. Storer et al. (2017) showed that *X. crassiusculus* has a high level of hidden genetic variation worldwide, even though its external morphology looks very similar across populations. Inbreeding systems promote localized adaptation expressed in behaviour, physiology, or symbiont interactions rather than external morphology. Covre et al. (2021) added that adaptation often manifests in phenology rather than form: Southern Brazilian populations exhibited two flight peaks, while Amazonian populations flew continuously year-round. These results together highlight that ecological plasticity and cryptic divergence occur beneath a conserved phenotype.

Hulcr and Stelinski (2017) link this pattern to the evolutionary stability of ambrosia symbiosis. They argue that mycangia constrain external morphology because successful fungal farming depends on precise anatomical structures. While ecological roles can shift (e.g., from dead to living tissues), the morphology of mycangia and associated pronotal/declivital features remains conserved. Thus, pest emergence in ambrosia beetles reflects symbiont ecology and host stress interactions more than visible morphological divergence.

The paradox of *X. crassiusculus*, morphological conservatism coupled with ecological plasticity and cryptic diversity, has direct implications for forest health. Conserved traits ensure reliable identification: the same declivity and pronotal characters have been applied consistently across Asia, Europe, and the Americas (Gallego et al. 2017; Thube et al. 2022). Yet this stability conceals significant ecological novelty. The species has expanded onto >200 host species in >60 families (Covre et al. 2021), adopted new behaviours such as kernel infestation (Thube et al. 2022), and exhibits hidden genetic structuring (Storer et al., 2017), all without external morphological change.

Hulcr et al. (2017) emphasised that pest potential lies in ecological traits rather than morphology, particularly the preadaptation to colonize living trees. Hulcr and Stelinski (2017) further argued that while most ambrosia beetle–fungus complexes are benign, a minority

cause serious damage through virulent symbionts, mass colonisation of stressed hosts, or wood staining. *X. crassiusculus* falls into the second category, where its strong attraction to ethanol and its stable boring phenotype facilitate outbreaks in nurseries and plantations. Morphological conservatism, therefore facilitates reliable taxonomy but cannot be assumed to predict pest impact.

For management, this implies that even if the morphology remains stable, the ecological roles or impacts of the species may still change. Morphological identification should be complemented by ecological monitoring and molecular/symbiont screening. Routine surveys should continue to use declivity and pronotal traits for sorting, but managers must remain alert to ecological or genetic shifts hidden beneath a conservative phenotype. This integrative perspective, linking morphology, ecology, and symbiosis, offers the most reliable framework for anticipating when a morphologically “stable” beetle may express new pest behaviours.

4.3.3 Applied Implications

The results of this study demonstrate that both the diversity and morphological variation of ambrosia beetles in Sarawak are strongly shaped by ecological context and evolutionary constraints, with direct consequences for pest management and biosecurity.

From a diversity perspective, monoculture plantations such as LPF42 fostered dominance by disturbance-tolerant generalists like *Xylosandrus crassiusculus*, whereas mixed planting systems such as Sabal FR supported more even and diverse assemblages. These findings, consistent with studies in Southeast Asia, Brazil, and Florida, emphasize that management intensity and surrounding land use restructure beetle assemblages. Environmental drivers, including stand age, humidity, and rainfall, further influenced abundance and species turnover. Such patterns highlight the importance of structural and host diversity for sustaining balanced beetle communities and reducing pest outbreaks.

From a morphological perspective, interspecific boundaries were clearly defined by body size and declivity/pronotal traits, which remain robust diagnostic features across regions. However, *X. crassiusculus* exhibited remarkable morphological conservatism across sites and continents, even as it expanded onto more than 200 host species and displayed new ecological behaviours such as kernel infestation in India. This stability

reflects stabilising selection on tunnelling and mycangial traits, yet masks cryptic genetic divergence, ecological plasticity, and symbiont-driven novelty (e.g., shifts in host use, phenology, and pest impact). Consequently, stable morphology does not equate to stable ecology. By integrating ecological, morphological, and evolutionary insights, plantation managers can develop more resilient monitoring frameworks and proactive pest management strategies, ensuring greater forest health and sustainability in Sarawak's industrial plantations.

These applied implications not only highlight the ecological and management relevance of ambrosia beetle diversity and morphology in Sarawak's plantations, but also provide the foundation for the broader conclusions and recommendations presented in the next chapter.

CHAPTER 5:

CONCLUSIONS

5.1 Conclusions

In conclusion, a total of 129 Ambrosia beetles representing seven species were recorded in LPF42, while 41 individuals from 11 species were collected in Sabal FR. Although overall abundance was highest in LPF42, ambrosia beetles were most frequently captured in plots planted with *Acacia mangium* across both study sites. *Xylosandrus crassiusculus* demonstrated a strong response to ethanol-baited traps and emerged as the most dominant species. The Shannon–Wiener and Simpson’s diversity indices were highest in Sabal FR, indicating a moderate level of species diversity. However, species evenness was low at both sites, suggesting dominance by a few species within the assemblages.

The morphological analyses revealed clear interspecific differentiation among ambrosia beetles, supported by both quantitative and qualitative traits. Quantitative analyses (PCA, PERMANOVA, SIMPER) showed that body length and pronotum width were the strongest contributors to species-level separation, with *X. ferrugineus* distinguished by its larger body dimensions. Qualitative traits, particularly those associated with the antennal club, pronotal slope, and elytral declivity, proved equally diagnostic. PCoA and PERMANOVA confirmed that these traits reliably separated species into distinct clusters, while SIMPER highlighted declivity and pronotal characters as the main contributors to dissimilarity. Collectively, these findings demonstrate that quantitative traits capture size-related variation, whereas qualitative traits emphasize discrete structures that are taxonomically robust.

Importantly, *X. crassiusculus* exhibited marked morphological conservatism, with both quantitative and qualitative traits showing stability across sites, consistent with previous studies documenting its uniformity across continents. In contrast, species such as *X. affinis* display pronounced sexual dimorphism and morphological integration, underscoring that

ambrosia beetles can follow different evolutionary trajectories. This duality highlights the importance of integrating multiple morphological approaches for accurate species delimitation and ecological interpretation.

This study has provided valuable insights into the diversity and morphological variation of ambrosia beetles in plantation forests of Western Sarawak. By examining species composition and trait-based variation across two contrasting sites, Sabal FR and LPF42, the research successfully addressed the objectives of documenting beetle diversity and assessing morphological differences within and between species. Sabal FR, which contains a mixture of indigenous and exotic tree species, supported a more diverse and evenly distributed beetle assemblage. In contrast, LPF42 recorded lower diversity and higher species dominance, likely influenced by its simpler plantation structure and surrounding oil palm matrix. These conditions are known to reduce habitat complexity and limit resource availability, often resulting in the dominance of generalist or disturbance-adapted species such as *X. crassiusculus* (Foster et al., 2011; Koh & Wilcove, 2008; Savilaakso et al., 2014).

Importantly, this study fills a critical knowledge gap in the documentation of ambrosia beetle diversity and morphological variation within plantation landscapes of Western Sarawak, a region where baseline data remain limited despite increasing plantation development. By providing quantitative diversity metrics and trait-based morphological analyses across contrasting plantation systems, the research establishes a foundational reference for future ecological, taxonomic, and pest risk studies in Sarawak. The integration of multivariate morphology further contributes methodological value by demonstrating that species-level boundaries can be robustly resolved using complementary quantitative and qualitative characters.

Beyond its taxonomic contribution, the findings have practical implications for forest management. The documented dominance of *X. crassiusculus* under simplified plantation conditions highlights the vulnerability of structurally homogeneous systems to disturbance-adapted ambrosia beetles. Conversely, the higher diversity recorded in Sabal Forest Reserve underscores the ecological importance of structural heterogeneity in maintaining more balanced beetle assemblages. Collectively, these results contribute to a better understanding of how plantation design, vegetation complexity, and habitat structure influence ambrosia beetle communities in tropical forest systems.

5.2 Recommendations

Based on the findings of this study, several recommendations are proposed to support future research and strengthen ambrosia beetle monitoring and management in forest plantations.

Firstly, it is recommended that long-term monitoring programmes be established using standardised ethanol-baited traps across different plantation types and over multiple seasons. This approach will help detect seasonal trends and population fluctuations, enabling early warning for pest outbreaks and contributing to more responsive and sustainable forest management (Stilwell et al., 2014).

Future studies should also consider expanding sampling coverage beyond exotic plantations to include natural forests, secondary growth areas, and reforested sites. Sampling across a broader spectrum of vegetation types will provide deeper insights into how beetle communities respond to different forest structures and ecological conditions. Such comparisons are essential for understanding species adaptability and could help predict shifts in assemblage patterns under changing land use scenarios (Tarno et al., 2022; Hulcr et al., 2007).

While morphological traits have proven useful for species identification in this study, incorporating molecular tools, particularly DNA barcoding, would enhance species resolution. This is especially important for identifying cryptic species or immature stages that may lack diagnostic external features (Gomez et al., 2018; Vanderpool et al., 2018). Combining morphological and molecular approaches would strengthen the accuracy of taxonomic and ecological assessments.

In addition, more targeted research is needed on Platypodinae species. The limited number and site-specific nature of Platypodinae recorded in this study highlight the need for focused investigations into their host tree associations, larval galleries, and fungal symbionts. Such information could reveal key aspects of their life histories, ecological functions, and pest potential (Wood, 1982; Vanderpool et al., 2018).

Finally, the study underscores the importance of integrating beetle diversity and morphological data into pest risk assessment frameworks. The dominance of *X. crassiusculus* and the presence of other potential pest species suggest that ambrosia beetles could pose a threat under certain plantation conditions. Incorporating taxonomic data into

integrated pest management strategies would allow for more targeted control efforts, particularly in plantation systems susceptible to beetle–fungal complexes and wood-boring damage (Hulcr & Stelinski, 2017).

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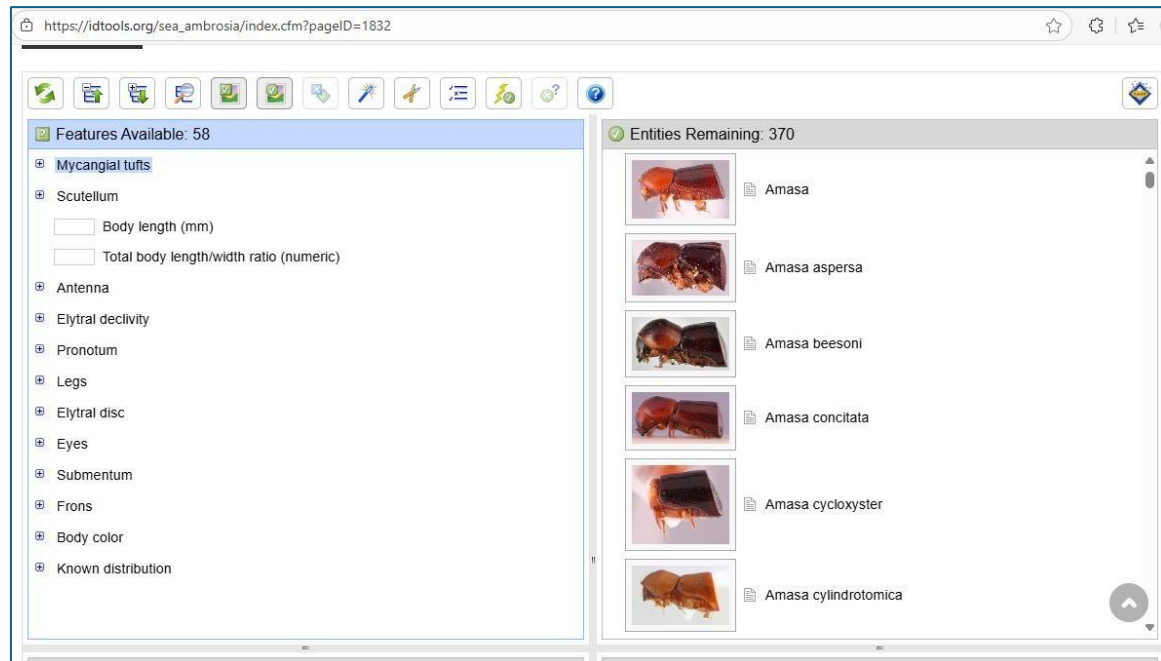
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APPENDICES

Appendix 1: Screenshot of the Southeast Asian Ambrosia Beetle ID tool interface for Scolytinae subfamily



Appendix 2: Screenshot of the Southeast Asian Ambrosia Beetle ID tool interface for Platypodinae subfamily

