Please cite this article as:

Yahya M.Q., Setiawan Y., Hadi M.S., Tarno H. Spatial dynamics of ambrosia beetle infestations in avocado orchards: a geostatistical approach from Indonesia. Journal of Plant Protection Research. DOI: 10.24425/jppr.2026.3234

Original article

Spatial dynamics of ambrosia beetle infestations in avocado orchards: a geostatistical approach from Indonesia

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Received: October 20, 2025

Accepted: January 16, 2026

Online Pree-Proof Publication: January 27, 2026

Responsible Editor: Janina Gospodarek

DOI: 10.24425/jppr.2026.3234

Abstract

Ambrosia beetles (Coleoptera: Scolytinae and Platypodinae) represent a significant threat to tropical agroecosystems, yet their spatial ecology in Indonesian avocado orchards remains poorly understood. This study presents the first spatially explicit assessment of ambrosia beetle infestation patterns in East Java, integrating field surveys with geostatistical analyses. Using RStudio and spatial tools including kernel density estimation (KDE), density-based spatial clustering of applications with noise (DBSCAN) clustering, and Getis-Ord Gi^* statistics, this research was aimed to distinguish spatial clusters, evaluate environmental correlates such as sunlight exposure, infestation holes vertical level position based on tree trunk, and recognize tree trunk diameter-related preferences in colonization of the ambrosia beetles. Results revealed strong spatial aggregation of beetle attacks, with significantly higher infestation intensity observed in trees exposed to prolonged sunlight, infestation holes located in upper trunk positions, and possessing larger tree trunk diameters. Global Moran's I and LISA statistics confirmed significant clustering, validating the influence of orchard microheterogeneity on beetle colonization. These findings underscore the importance of integrating spatial analysis into pest management strategies and offer a replicable framework for monitoring cryptic pests in other tropical cropping systems.

Keywords: ambrosia beetles, avocado orchard, spatial analysis, kernel density estimation, DBSCAN

Introduction

Ambrosia beetles (Coleoptera: Scolytinae and Platypodinae) are among the most destructive pests of woody plants in tropical and subtropical agroecosystems, including avocado orchards (Crane *et al*. 2008). In Indonesia, ambrosia beetles were reported to attack Angsana (*Pterocarpus indicus*) trees in Malang City, East Java (Tarno *et al*. 2014) and cacao plantations in Luwu District, South Sulawesi (Nuriadi *et al*. 2023). To date, there have been no reports of ambrosia beetles attacking avocado orchards in Indonesia. However, previous studies have reported that ambrosia beetles were captured using ethanol-baited traps in avocado orchards and several other fruit orchards in East Java (Tarno *et al*. 2025a, 2025b). Ambrosia beetles exhibit a unique symbiotic relationship with mutualistic fungi, which they cultivate within host trees to serve as their primary food source (Harrington 2005). Females initiate colonization by boring into host tissues and inoculating fungi from their mycangia (Marchioro *et al.* 2020). Stressed or weakened hosts are preferred by ambrosia beetles, however, several species as aggressive invaders can attack healthy trees and cause significant economic losses (Ranger *et al*. 2013).

Avocado is a popular and widely consumed fruit in Indonesia. Avocado production in Indonesia increased from 865,780 tons in 2022 to 919,509 tons in 2024, representing an increase of 53,729 tons over the two-year perood (Irjayanti *et al*. 2025). The increase in avocado production indicates its potential to become an important commodity and requires further development to meet future Indonesian domestic market demand. However, ambrosia beetles have been reported to be serious pests in avocado orchards in Florida, USA and Mexico, suggesting that they may also pose a potential threat to avocado plantations in Indonesia (Mann *et al*. 2011; Lira-Noriega *et al*. 2018). The complexity of ambrosia beetle behavior and its relations to fungal pathogens need a strong understanding about patterns of spatial distribution and host preferences in the local environment to facilitate early detection and effective management (Zanuncio *et al.* 2005; Henriques *et al.* 2006; Hofstetter *et al.* 2015). Knowing the infestation pattern of a pest or disease pathogen can be a good first step in understanding the management of that pest and disease pathogen (Tran *et al*. 2017).

Based on the current studies, the activity of ambrosia beetles is habitually non-random and deeply affected by microclimatic factors, tree shape, sunlight exposure and stem diameter (Byers 1996; Lettenmaier *et al.* 2022). In the example, ethanol emissions from sun-exposed or water-stressed trees work as potent olfactory cues that help aggregation of the beetles, often producing clustered infestations or "hotspots" within orchards. Additionally, vertical stratum of occurrence sites and preference for larger diameter hosts have been known in several scolytinae species (Ranger *et al*. 2013; Gomez and Hulcr 2019), suggesting that colonization of ambrosia beetles is exceedingly controlled both spatially and behaviorally.

Recently, there have been no published reports that applied spatially explicit methods, such as kernel density estimation (KDE), density-based spatial clustering of applications with noise (DBSCAN) clustering, and Getis-Ord G*i** analysis to evaluate the dynamics of ambrosia beetle attacks on an avocado orchard in Indonesia. Based on this, data from this study can also provide the current status of the condition of avocado commodities (Damos *et al*. 2020). The use of geospatial tools has been verified to be useful for pest distribution mapping, classifying risk zones, and notifying targeted management strategies in other cropping systems (Ranger *et al*. 2013; Menocal *et al.* 2020). This insect dynamics analysis can be used not only for insect pests, but also to determine predator dynamics and as a basis for determining plantation management (Wains *et al*. 2010; Trzciński and Piekarska-Boniecka 2013).

The aim of this study was to analyze ambrosia beetle infestations on avocado plantations using a geospatial approach and to observe ambrosia beetle preferences based on the conditions of the avocado trees (sunlight exposure, height of the ambrosia beetle infestation holes in the tree trunk, and trunk diameter). A mixture of geostatistical and non-parametric statistical approaches was conducted to examine the spatial dynamics of ambrosia beetle attacks on an avocado orchard in this study.

Materials and Methods

Study sites

The study was conducted in the UB Forest, located in Karangploso, Malang Regency, East Java, Indonesia (Fig. 1). The research was conducted at three sites, namely Tawangargo (242.11 ha; areas no. 1–7), Donowarih (181.58 ha; areas no. 8–11), and Bocek (121.05 ha; areas no. 12–16). Across these sites, a total of 135 avocado (*Persea americana* Mill.) trees were identified and monitored. Observation sites were selected through preliminary field surveys that confirmed the presence of beetle-infested avocado trees. Since avocado is not a dominant crop in the UB Forest and is primarily grown as an intercrop, all available avocado trees were included in the study to ensure comprehensive coverage of the limited population.

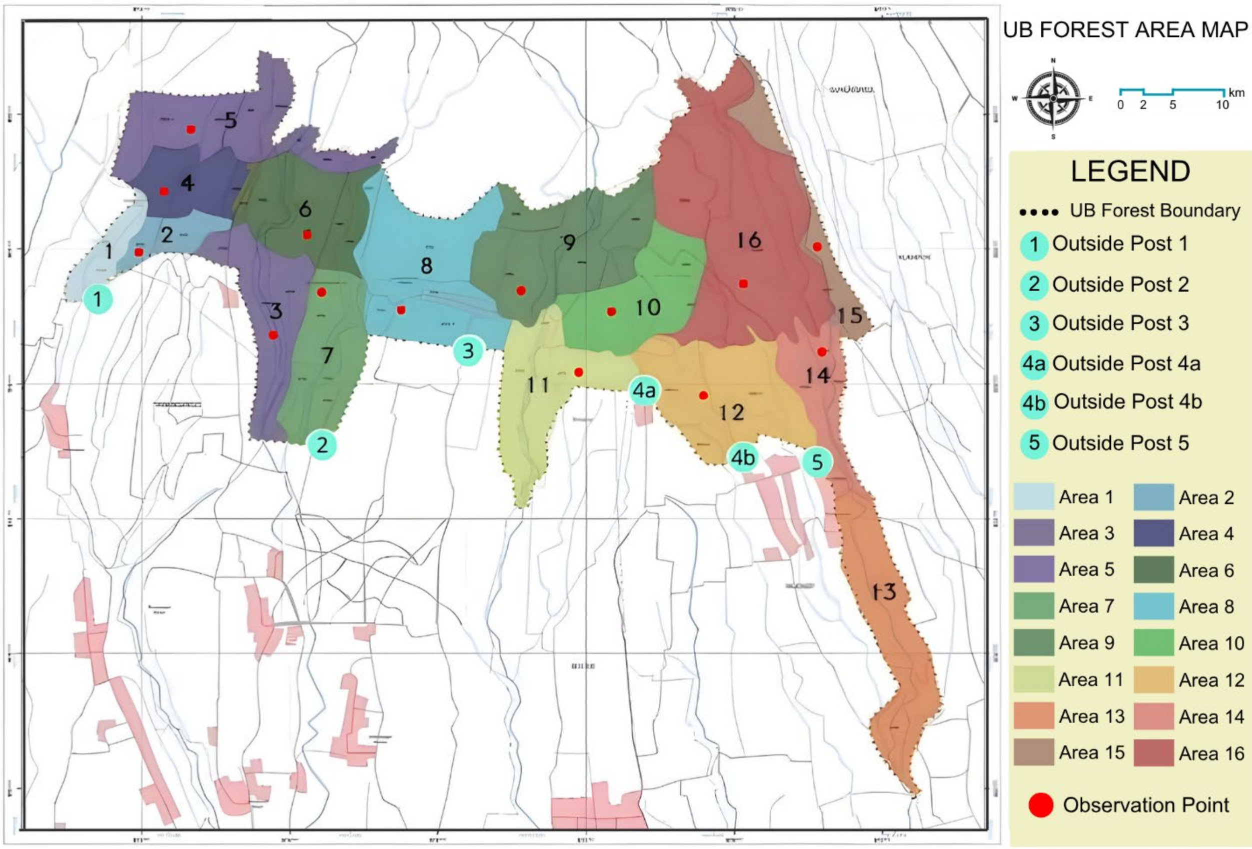

Fig. 1. Map of observation points in Karangploso, Malang Regency, East Java, Indonesia (UPT PKH UB Forest, 2016)

Field observation

Avocado trees were observed weekly for 12 weeks (60 observations) to document the characteristics of damage caused by ambrosia beetle infestation. This observation duration corresponded to the beetle's typical life cycle, which includes locating a host, boring galleries, reproduction, and oviposition, typically completed within seven weeks (Gómez *et al*. 2012). Symptoms of infestation, such as trunk gallery formation and foliar wilting, were recorded and used to assess damage severity.

To determine the health status of trees, the number of branches and branches with wilted or fallen leaves was counted. Tree health status was classified into five categories based on the proportion of wilted or fallen leaves: healthy (0% damage), lightly infested (10–25%), moderately infested (26–50%), severely infested (>50%), and dead trees showing signs of infestation.

To evaluate beetle hole patterns, counts were conducted on trees categorized as infested or dead. Over a period of 12 weeks, each avocado tree was observed for the number of holes resulting from ambrosia beetle infestation. Hole locations were recorded relative to sunlight exposure, categorized as either high (exposed to sunlight more than six hours a day) or low/no exposure (exposed to sunlight for a maximum duration of six hours per day or not exposed to sunlight at all). In addition, vertical distribution of entry holes was documented based on three trunk height intervals: 0–50 cm, 51–75 cm, and 76–150 cm above ground level. Trunk diameter was also recorded, and trees were classified into three size categories: small (15–40 cm), medium (41–65 cm), and large (66–90 cm) to assess whether trunk girth influenced beetle infestation intensity.

Beetle specimens were extracted from infested avocado trees by cutting trunk segments containing gallery holes using saws and chisels. These avocado wood segments were then carefully split open to locate the beetles inside. Confirmed specimens were preserved in 1.8 mL cryo tubes containing 90% ethanol and labelled with collection date and location. Morphological identification was conducted using a digital microscope (1600× magnification) and Olympus SZX7 stereo microscope (Olympus Corporation, Tokyo, Japan).

Data analysis

To evaluate differences in infestation intensity, entry hole numbers across trunk heights, and trunk diameter categories, a Saphiro-Wilk normality test was performed, followed by analysis of variance (ANOVA). An independent t-test was used to compare hole distribution based on sunlight exposure intensity.

Kernel density estimation (KDE) was used to visualize the spatial clustering of beetle entry holes and to identify infestation hotspots. The analyses were conducted using the *vegan* package (Oksanen *et al*. 2025), *ggplot2* (Wickham 2016), and *spatstat* (Baddeley 2015). The *sf* package was employed to manage spatial vector data for mapping the research location layout and tree positions (Pebesma 2018).

Density-based spatial clustering of applications with noise (DBSCAN) was performed using the *dbscan* package (Hahsler *et al*. 2019), allowing trees to be classified into infestation clusters and spatial outliers to be identified. Spatial autocorrelation analyses were conducted using the *spdep* package (Bivand & Wong 2018), including Global Moran's I and Local Indicators of Spatial Association (LISA), such as the Getis-Ord G*i** statistic.

Data wrangling and preparation were carried out using *dplyr* and *tidyr* (Wickham *et al*. 2025), enabling efficient manipulation of infestation datasets. Enhanced boxplots with statistical annotations (e.g., Wilcoxon and Kruskal-Wallis tests) were generated using *ggpubr* (Kassambara 2025). The *viridis* package was used to provide color palettes suitable for scientific visualization, ensuring clarity in density and cluster maps (Garnier *et al*. 2014).

Finally, *ggmap* (Kahle & Wickham 2013) and *ggspatial* (Dunnington 2025) were used to add basemap overlays and spatial context for visualizing KDE and clustering results. All statistical analyses were conducted using RStudio version 1.1.463 (Posit Team, 2025).

Results

Symptoms of an avocado tree infested with ambrosia beetles

Based on observations, the symptoms on avocado trees were caused by ambrosia beetles belonging to the subfamilies Platypodinae and Scolytinae (Fig. 2). During the observation period, two genera of ambrosia beetles from Scolytinae (*Euwallacea* and *Xylosandrus*) and two from Platypodinae (*Treptoplatypus* and *Dinoplatypus*) were found on avocado trees. The first symptom of an ambrosia beetle infestation is the appearance of holes in the avocado tree trunk (Fig. 2A). Holes caused by ambrosia beetle infestation are characterized by the presence of frass emerging from the holes. The frass can be noodle-like, which is an elongated, cylindrical frass (Fig. 2B) or powder-like (Fig. 2A). These holes can serve as entry points for pathogens, potentially infecting the avocado tree. The invading pathogen can alter the physiology of avocado tree trunks, as evidenced by discoloration (Fig. 2D and 2E). If the bark and wood of an affected avocado tree are removed, gallery tunnels created by the burrowing of ambrosia beetle adults will be visible (Fig. 2F). Severe ambrosia beetle infestations can kill avocado plants (Fig. 2C).

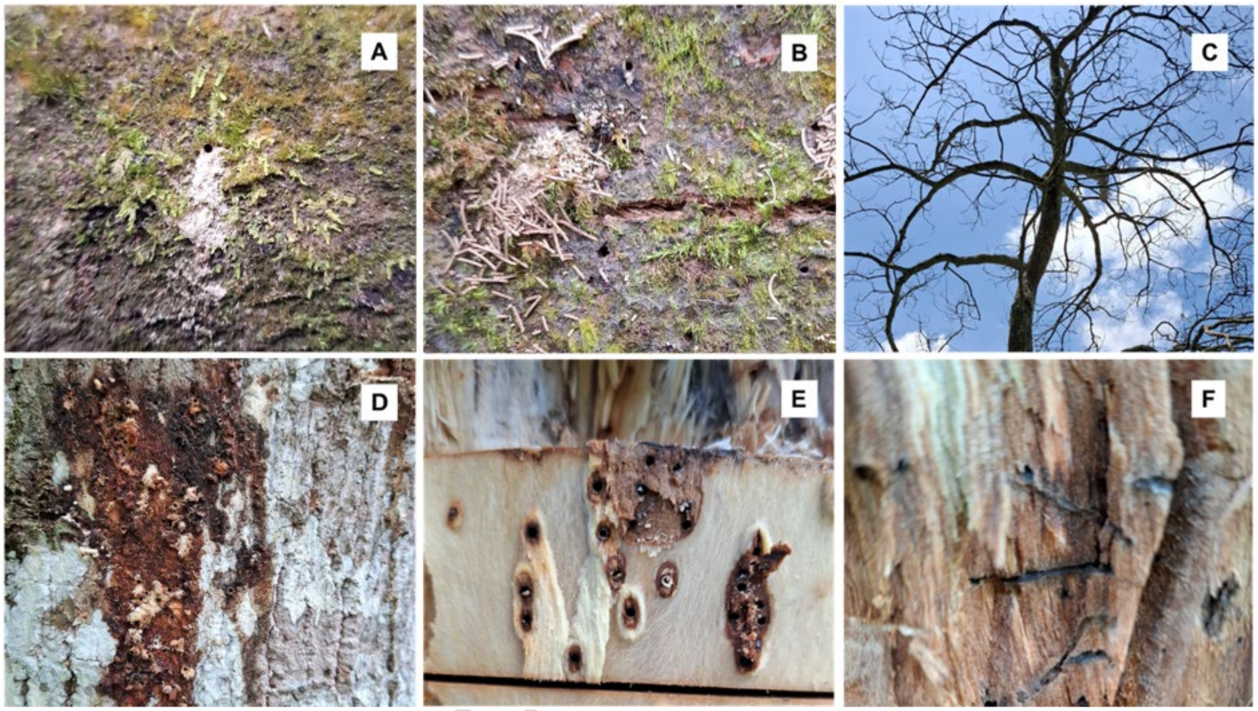

Fig. 2. Symptoms of ambrosia beetle infestation. A) holes with powdery frass, B) holes with noodle-like frass, C) dead avocado tree, D) discolored bark, E) discoloration around the holes caused by the infestation, F) gallery tunnels

Spatial infestation patterns (KDE + DBSCAN + G*i**)

The spatial distribution of ambrosia beetle attacks in the avocado orchard was shown in the kernel density estimation (KDE) map (Fig. 3). Two prominent hotspots were identified: one in the southwestern and another in the northeastern section. These areas exhibited the highest density values, with infestation peaks exceeding 40,000. This means that many avocado trees in both hotspots are experiencing intense ambrosia beetle infestation. The density level range (10,000-40,000) is relative and is used to identify areas with low to high infestation density, not as an absolute measure of the number of holes per unit area. The red circles, scaled to the number of entry holes per tree, indicate both the intensity and frequency of attacks. In contrast, trees in the central and southern zones experienced sparse and scattered infestations.

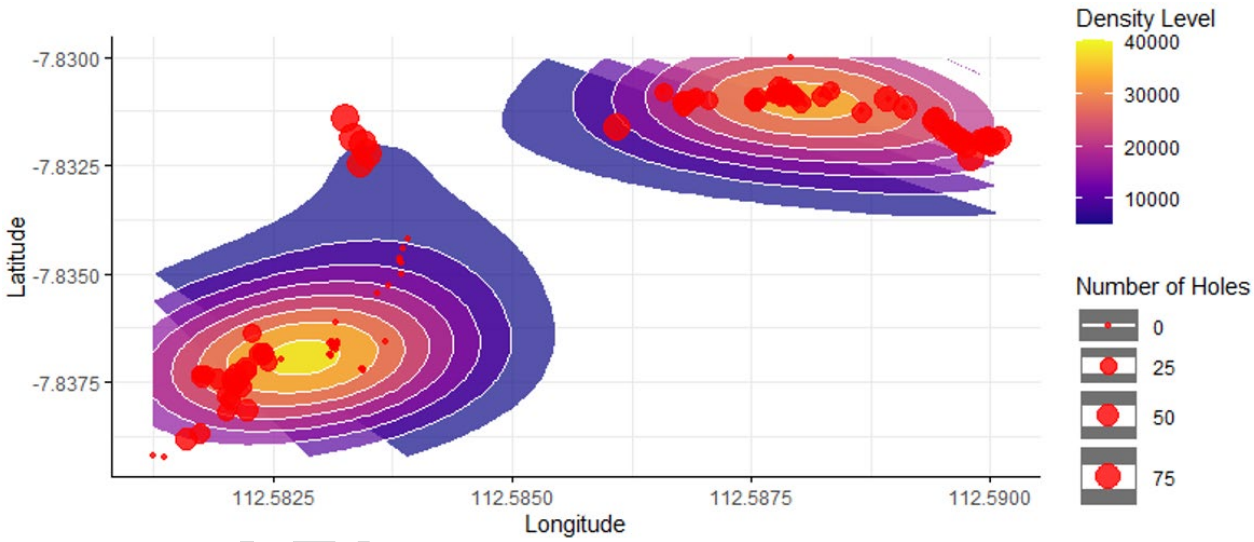

Fig. 3. Kernel density estimation (KDE) map showing the spatial distribution of ambrosia beetle attacks on avocado trees. The color gradient represents density levels of infestation intensity, with yellow areas indicating high-density clusters and purple areas indicating low-density regions. Red points represent individual trees, and point sizes are proportional to the number of entry holes

DBSCAN clustering further elucidates the spatial organization of attacks, identifying five discrete clusters (Fig. 4). Clusters 1 and 2 correspond to the major KDE hotspots and represent the most heavily infested areas. Cluster 3 comprises smaller-diameter trees with dense infestations, while Cluster 0 includes largely isolated attack events.

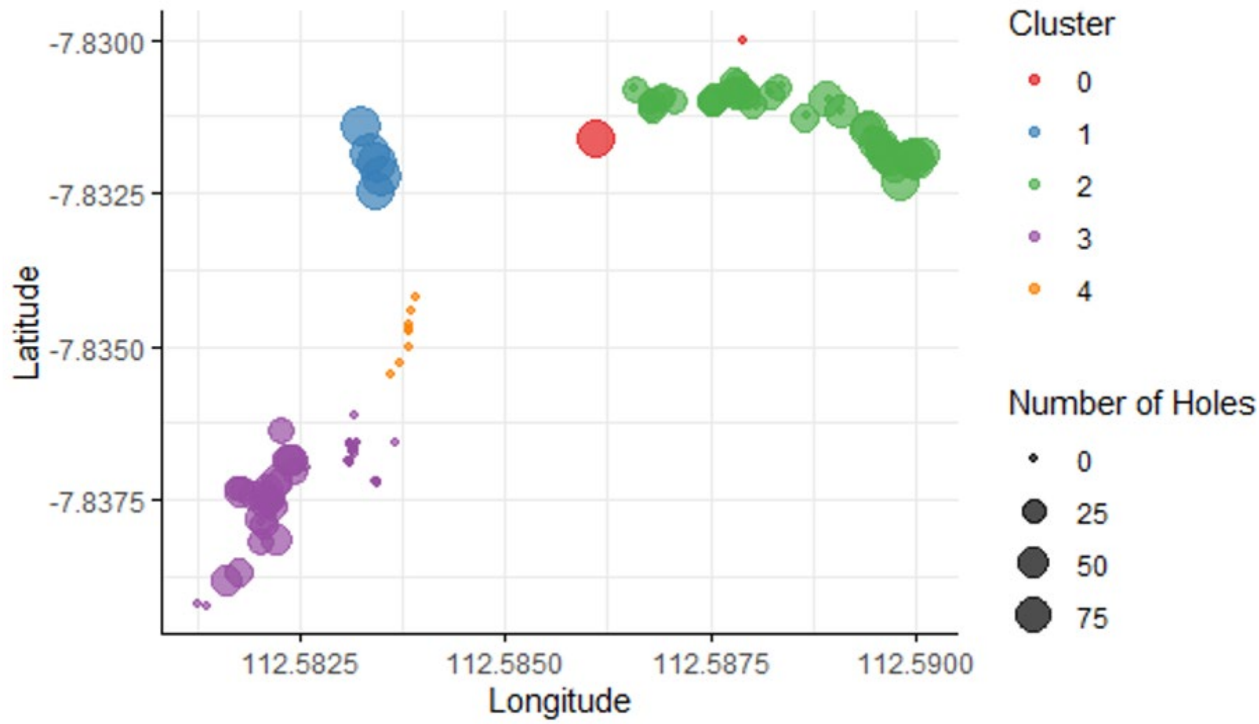

Fig. 4. DBSCAN-derived clusters (0–4) of ambrosia beetle attacks on avocado trees in the study area. Each point represents a tree, with the point size proportional to the number of attack holes. Cluster colors indicate spatially aggregated groups of infested trees, while outlier points (Cluster 4) denote isolated attacks not assigned to any cluster

The Getis-Ord G*i** analysis validated the KDE and DBSCAN results by statistically delineating significant hotspots ($Gi^* > 2$, *p-value*< 0.05) and cold spots ($Gi^* < -2$, *p-value*< 0.05) (Fig. 5). Hotspots were consistent with the southwestern and northeastern zones, while cold spots were centered in the orchard's interior and southern regions. The positive global Moran's I value (I = 0.610, *p-value*< 2.2e16) further confirms non-random aggregation and spatial autocorrelation in infestation patterns.

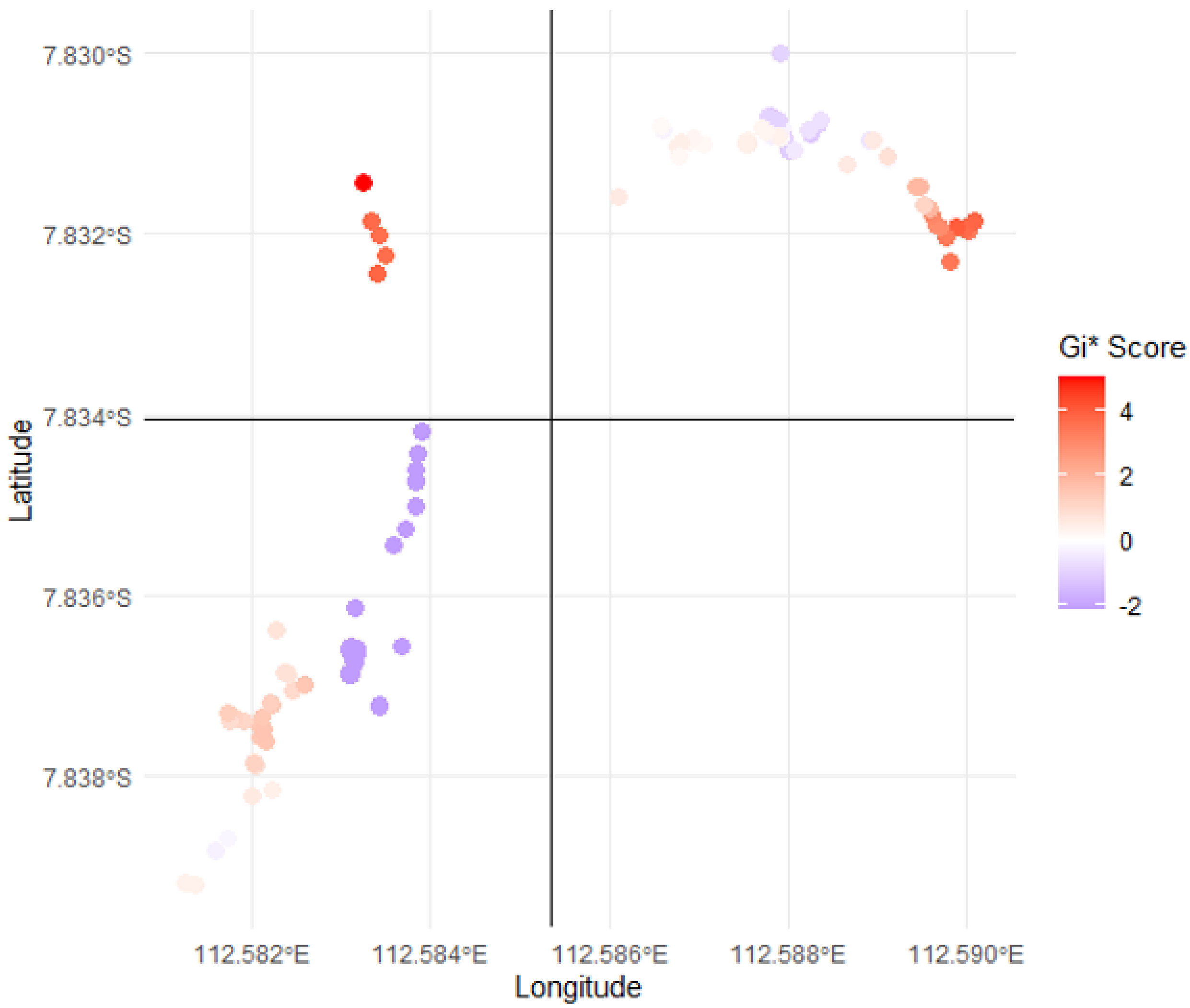

Fig. 5. Spatial distribution of ambrosia beetle attacks in an avocado orchard. Red points indicate significant hotspots (G*i** > 2, *p-value*< 0.05), blue points denote cold spots (G*i** < -2, *p-value*< 0.05), and white points represent areas with no significant clustering. Kernel density estimation (KDE) overlays illustrated areas of high and low infestation density.

Environmental drivers (sunlight, vertical position, and tree's diameter)

Sunlight exposure

As shown in Fig. 6, avocado trees receiving prolonged sunlight exhibited significantly greater ambrosia beetle attack intensity than those with limited exposure (median = 22), confirmed by T-test (t = 7.3884, *df*= 137.69, *p-value*= 1.298e11). These results suggest that increased solar radiation may intensify physiological stress, enhancing tree attractiveness through elevated volatile emissions.

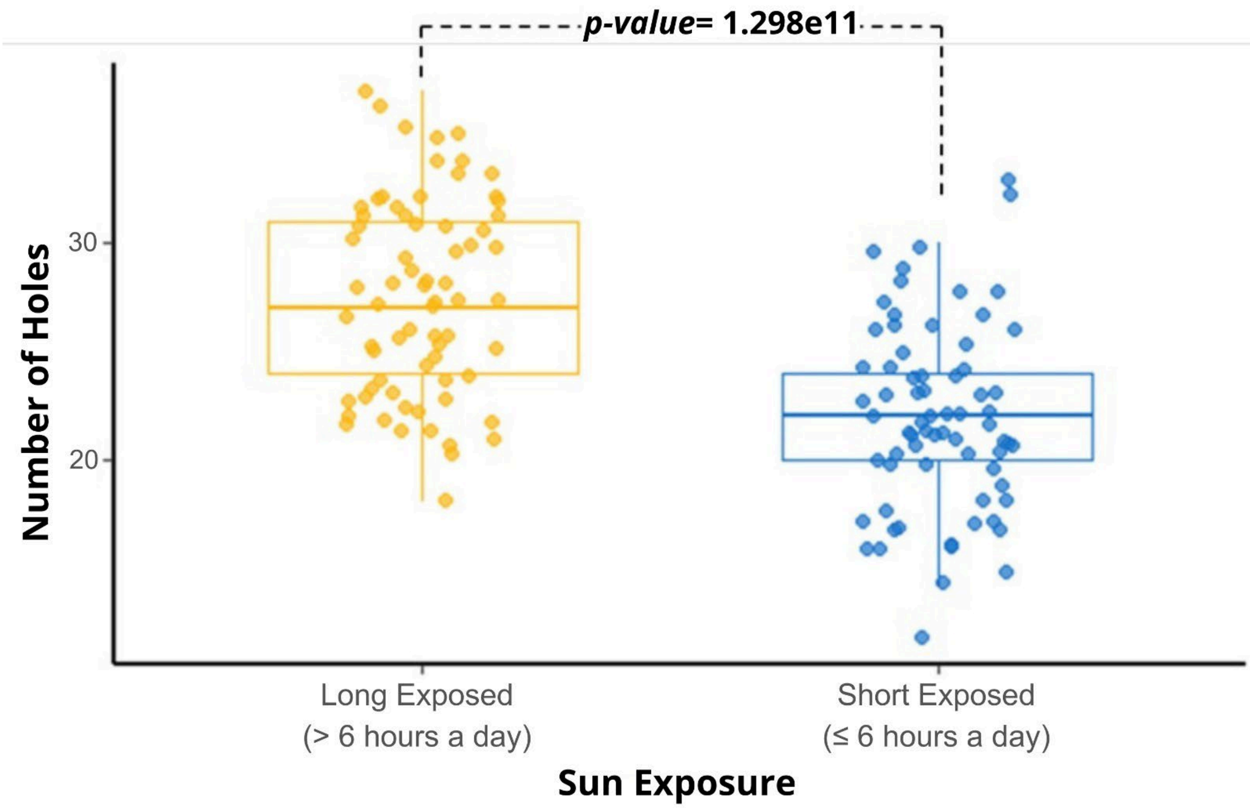

Fig. 6. Comparison of ambrosia beetle attack intensity on avocado trees under different sun exposure durations (t = 7.3884, *df*= 137.69, *p-value*< 0.001)

Vertical Stratification

Vertical distribution analysis revealed that entry hole density was highest in the upper (High) sections of avocado trees (median = 20), significantly exceeding Medium and Low zones (ANOVA with *p-value*< 0.001, and Tukey HSD) (Fig. 7). This vertical stratification suggests a beetle preference for elevated positions within the canopy.

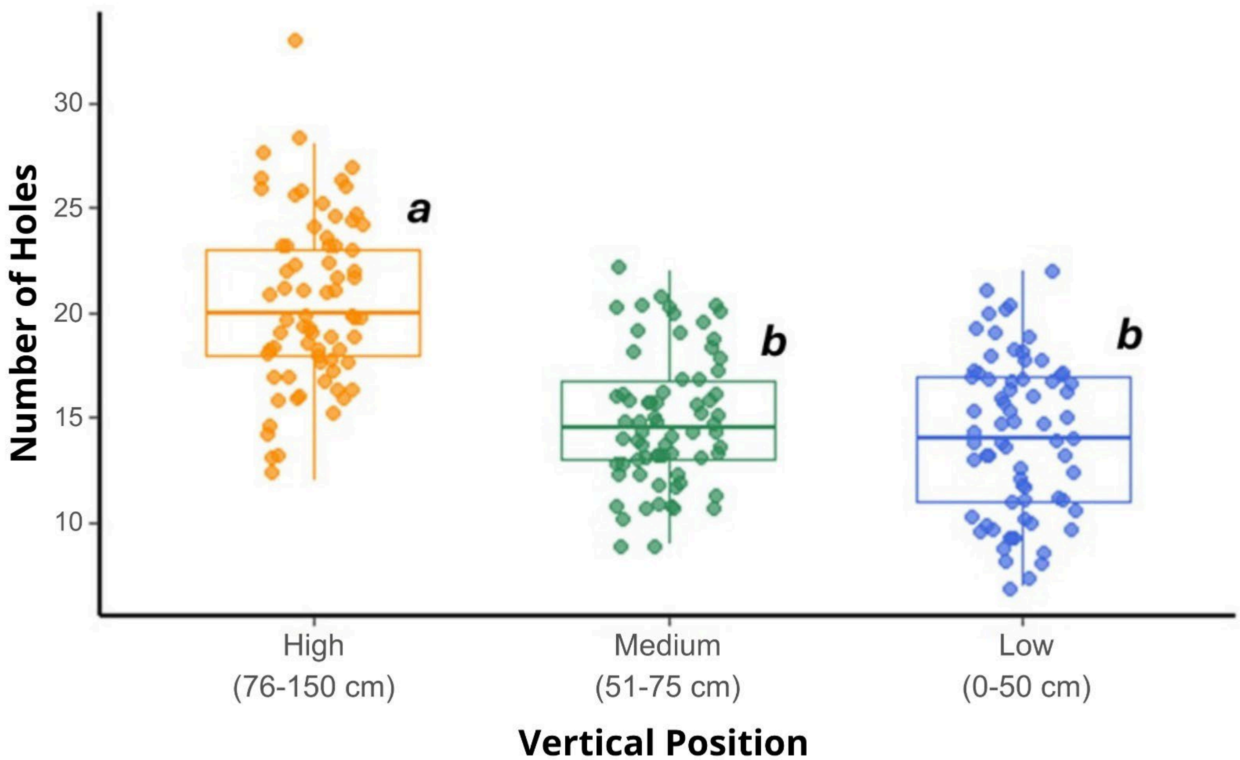

Fig. 7. Boxplots showing the number of ambrosia beetle entry holes across three vertical positions on avocado trees (ANOVA with *p-value*< 0.001; and Tukey HSD)

Tree's diameter

Tree size also significantly influenced infestation severity (Fig. 8). Large-diameter trees (big and medium sizes) were more heavily attacked than small (median = 15) individuals (*p-value*< 0.001).

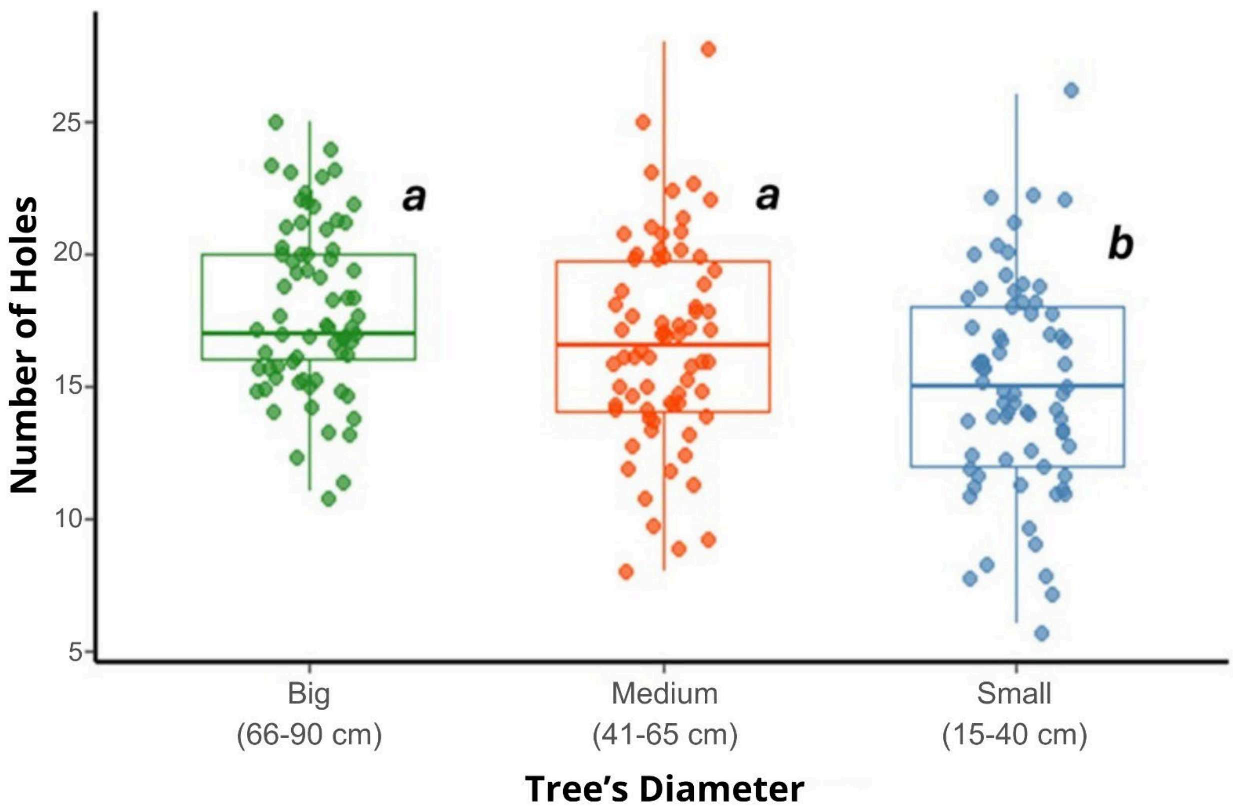

Fig. 8. Boxplots showing the number of ambrosia beetle entry holes across avocado tree diameter categories (ANOVA with *p-value* < 0.001, and Tukey HSD)

In this study it was found that the number of ambrosia beetle entry holes differed across avocado tree diameter categories (Fig. 8). A larger diameter of tree provided a higher number of entry holes than the medium and small diameters. The size of the stem diameter can also reflect the age of the plant. This finding indicated that tree size, as reflected in trunk diameter, was an important factor influencing susceptibility to ambrosia beetle infestation. In practical terms, larger trees should be prioritized in monitoring regimes and may benefit from targeted repellents or trap placement. Early detection in these vulnerable individuals can prevent infestation buildup and reduce the overall pest load in the orchard.

Discussion

Symptoms of avocado tree infested by ambrosia beetles

The observed symptoms of ambrosia beetle infestation on avocado trees are similar to those reported for *Pterocarpus indicus* trees in Thailand (Bumrungsri *et al.* 2008), and Indonesia (Tarno *et al.* 2016). Based on this study, symptoms of ambrosia infestation included frass emerging from the burrowing holes. *Pterocarpus indicus* is one of the tree species attacked by *Euplatypus parallelus*, a species of ambrosia beetle from the subfamily Platypodinae, the same as the genera *Treptoplatypus* and *Dinoplatypus* that were commonly found during sampling in this study. Two types of frasses appear: the first is powdery, and the other is elongated, resembling toothpicks. Based on Tarno *et al.* (2011), the elongated (fibrous) frass resulted from adults during the initiation step, and powdery frass was produced by larvae in the next step. The burrowing holes turn blackish at the edges over time. Infestation by ambrosia beetles can cause the leaves of affected plants to wilt, then dry out, and eventually fall off. This can occur because there is a disruption in the distribution of nutrients and water caused by the plant's transport tissue, namely xylem and phloem, being damaged by attacks from ambrosia beetles (Mann *et al*. 2011).

Spatial infestation patterns (KDE + DBSCAN + Gi^*)

Two distinct infestation hotspots were identified, suggesting spatial aggregation of beetle attacks across the orchard. This strong spatial aggregation is consistent with the known ecology of scolytine beetles, which are attracted to volatile cues, especially ethanol emitted by physiologically stressed trees (Ranger *et al*. 2013). These hotspots are likely associated with microclimatic variations, such as elevated solar radiation and temperature, which can exacerbate tree stress and increase volatile emissions (Byers 1996; Lettenmaier *et al.* 2022). Conversely, areas of low density may reflect favorable conditions that reduce beetle colonization, including higher canopy cover due to controlled, less intensive branch pruning.

The value of visualizing spatial infestation gradients and recognizing priority zones for localized pest control are demonstrated by the KDE approach. Targeted felling, trap placement, and microclimate modulation as site-specific strategies could be installed to defeat beetle aggregation and decrease fungal spread.

The ambrosia beetle infestation, especially their spatial distribution pattern on avocado trees in the UB Forest, was described complementally by DBSCAN and Gi^* analyses. DBSCAN analysis identified five main spatial clusters of infestation (0–4), with the dot size representing the intensity of infestation based on the number of holes. These results suggest that infestation was not randomly distributed but rather was observed within specific tree groups, while outliers indicated that infestation was buffered outside the main clusters.

Meanwhile, Gi^* analysis emphasizes the statistical significance of spatial concentration of infestation. The results revealed significant hotspots with $Gi^* > 2$ and cold spots with $Gi^* < -2$. This pattern validated the DBSCAN results, as most of the high-intensity clusters also coincided with hotspot areas. Thus, these two approaches complemented each other. DBSCAN was effective in identifying the cluster structure of infestations, while Gi^* highlighted locations of high spatial significance that require special attention in pest management.

The main difference between the two lies in the resulting ecological interpretation. DBSCAN depicts patterns of infestation aggregation that tend to follow distributions within susceptible populations, while Gi^* provides quantitative confirmation that some of these aggregations are not mere coincidences but truly represent infestation hotspots. This is important in the context of pest epidemiology, as not all infestation clusters have the same impact on its spreading.

The combination of these two analyses demonstrated that ambrosia beetle infestations in the UB Forest were spatially heterogeneous, with some areas acting as active infestation centers and others remaining relatively unaffected. Practically, this information can be used to formulate more precise spatial-based control strategies, where interventions are directed at high-intensity hotspots while monitoring outliers that could potentially become sources of new infestations. The adaptive management of ambrosia and bark beetles in agroforestry and plantation can be provided by a specific approach which investigates the spatial infestation pattern (Wardhaugh 2014; MacEdo-Reis *et al.* 2016).

Environmental drivers (sunlight, vertical position, and tree's diameter)

Sunlight exposure

The interaction between sunlight exposure, tree condition, and ambrosia beetle infestation behavior is one possible ecological mechanism to describe this pattern. Trees which are exposed to more sunlight tend to be exposed to extreme microclimates, such as increased temperature and decreased moisture. These conditions can trigger physiological stress that drives the production of volatile compounds such as ethanol (Menocal *et al*. 2023). Ethanol is known to be a major attractant for various ambrosia beetle species (Beaver 2013). Accordingly, trees with high sunlight exposure become more attractive targets for infestation.

In contrast, trees with shorter exposure to sunlight have relatively stable physiological conditions that produce the low number of infestation holes. These findings are consistent with previous literature reporting that tree stress due to environmental factors, such as light intensity and temperature, contributes to increased susceptibility to ambrosia beetles and other wood borer attacks (Kitajima and Goto 2004).

These findings highlight the need to integrate plantation management and light distribution into pest control strategies based on a management viewpoint. Trees in areas with high light exposure should be selected for monitoring, as they may serve as potential entry points for infestation (Cambronero-Heinrichs *et al.* 2025). Silvicultural practices such as optimizing planting density, pruning, or introducing shade trees can reduce tree stress caused by excessive sunlight while simultaneously lowering infestation risk (Werle *et al.* 2014).

Vertical stratification

The pattern related to vertical stratification can be credited to several ecological mechanisms. The upper tree parts receive greater sunlight exposure, resulting in higher tissue temperatures and lower humidity. Such conditions can stimulate physiological stress in the trunk, stimulating the emission of volatile compounds (particularly ethanol) which act as an attractant for ambrosia beetles (Ranger *et al.* 2023). These results are associated with light exposure analyses showing a positive correlation between sunlight duration and infestation intensity (Tarno *et al.* 2014).

Additionally, microclimatic and physical factors contribute to this pattern. The upper canopy is generally more open and thus more easily detected by flying beetles searching for hosts. The ambrosia beetles also tend to attack exposed tree parts that provide strong visual and chemical cues (Tarno *et al*. 2016). In contrast, shaded lower parts protected by the canopy are relatively less attractive to infestation.

These results provide significant implications for monitoring and control. The upper part of trees should receive greater attention during inspections, as they may serve as the initial colonization points before infestation spreads to other parts of the same or neighboring trees (Gugliuzzo *et al.* 2021). Targeted monitoring focused on upper canopy areas can improve early detection efficiency and enhance management effectiveness (Rivera *et al.* 2020).

Tree diameter

Based on observations and data analysis, trees with medium to large trunk diameters exhibited higher levels of ambrosia beetle infestation. This pattern can be explained by several ecological mechanisms. Large-diameter trees generally have a larger volume of xylem tissue and nutrient reserves, which are better able to facilitate beetle populations and the development of their fungal symbiosis (Castrillo *et al*. 2016). Furthermore, older trees tend to experience physiological decline, including weakened chemical and physical defenses, which increase susceptibility to initial colonization and beetle gallery formation (Six and Wingfield 2011).

Large trunk size also enhances the visual and chemical attractiveness of beetles. Emission of volatile compounds due to wounding or physiological stress was generally higher in large-diameter trees, serving as chemical signals that attract and strengthen beetle aggregation (Seybold and Fettig 2021). This explains why infestation intensity was often concentrated in trees with larger diameters. Overall, these results confirm that stem diameter played a significant role in determining the level of ambrosia beetle infestation on avocado trees. This finding is consistent with previous studies on various tree species that reported a preference for attacks on individuals with larger stems (Mayfield and Brownie 2013). Practical implications for avocado orchard management should consider tree size as a risk indicator, so that large-diameter trees can be the focus of more intensive monitoring and control measures.

Conclusions

This study presents the first spatial analysis of ambrosia beetle attacks in Indonesian avocado orchards, revealing clear aggregation patterns linked to sunlight exposure, tree size, and vertical position. Using KDE, DBSCAN, and Gi* analysis in RStudio, infestation hotspots associated with stressed microhabitats were identified. These findings emphasize that beetle colonization was shaped by environmental heterogeneity and host traits, underlining the need for site-specific monitoring and targeted interventions. Results showed a strong spatial clustering of ambrosia beetle attacks, with significantly higher infestation levels noted in trees that received prolonged sunlight, were positioned in upper trunk areas, and had larger diameters. The applied spatial framework demonstrated the utility of precision pest management and offers a replicable model for other tropical agroecosystems. Geospatial data on ambrosia beetle attacks and preferences from this study are expected to be used as a basis for pest and disease management in avocado plantations. It is hoped that this initial study observing ambrosia beetle infestations using a geospatial approach can serve as a starting point for other related research topics.

Acknowledgements

We would like to thank Prof. Jiri Hulcr for identification of ambrosia beetles during a workshop of ambrosia and bark beetles from the School of Forest, Fisheries and Geomatics Sciences, University of Florida, Gainesville, Florida, USA in the Faculty of Agriculture, Universitas Brawijaya.

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