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RESEARCH

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Infestation patterns of a major wood boring pest, *Psiloptera fastuosa* (Buprestidae: Coleoptera) in Tasar, *Terminalia arjuna* (Myrtales: Combretaceae) plantation

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Abstract

Tasar silk is a significant cash crop in the tropics. In Tasar culture, arjuna (*Terminalia arjuna*) (Combretaceae) are often planted on farms because the Tasar worm largely consumes their leaves, *Antheraea paphia* (Lepidoptera: Saturniidae). The wood-boring *Psiloptera fastuosa* (Coleoptera: Buprestidae) causes severe threats to Tasar plantations during their mating season (September equinox to December solstice). After hatching, the coleopteran grubs puncture and penetrate the arjuna stem, mature into pupae inside, pass into adults, and exit through emergence holes, causing severe damage to younger plants. Though such infestations are highly fatal, no precautions have been proposed to protect the arjuna plantations. Therefore, sustainable Tasar plantation management is highly challenging because of limited bio-ecological information and the infestation pattern of the pest. This study investigates the origins and implications of *P. fastuosa* infestations in *T. arjuna* plantations. Our study focuses on seasonal changes in *P. fastuosa* assaults on its primary host and infestation frequency in an Indian agroecosystem. Second, we examined whether host plant age and size affected the *P. fastuosa* invasion. The occurrence and distribution of emergence holes for adult beetles on the arjuna bark and the intensity of wood galleries on the stem aid in assessing the beetle infestation. It was observed that 4 to 8-year-old arjuna plants wilted more frequently than younger (<4 years) and older (>8 years) plants. Since most infestations occur on the main trunks up to the middle of the plant's height during autumn, insecticidal treatments can be performed around the middle of the main trunks of 4–8-year-old arjuna plants during fall. The findings of this study will benefit the management and propagation of arjuna plants for tropical Tasar silk production.

Keywords Buprestid infestation, *Psiloptera fastuosa*, Tasar plantation, Pest management

Introduction

The cultivation of Tasar silk is a notable agricultural industry across several Southeast Asian countries, including China, Korea, Japan, and the Indian subcontinent (Dewangan 2013; Goel 2017; Nath et al. 2021; Arora and Gupta 1979; Peigler 1993). Tasar food plants can grow across a range of altitudes, from around 600 m above sea level (Khasru et al. 2018) to the Sub-Himalayan highlands (Sharma and Rai 2015); however, commercial Tasar production is frequently performed in hot and humid natural settings, employing both on-farm and

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off-farm approaches (Ojha and Panday 2004). Most of the Tasar moths have wide range of distributions, from dry landscapes to tropical rain forests (Renuka and Shamitha 2015) and can ingest a variety of wild foliage. Due to its recurring demand and usages (CSB 2020), Tasar silk cultivation has a significant impact on the economic, social, environmental, and cultural contexts of people's lives and professions in many Southeast Asian countries (Khasru et al. 2018; Sharma and Kapoor 2020; Sinha and Srivastava 2002; Sharma 2019).

Tasar silk is produced by the bivoltine silkworm *Antheraea paphia* (L.) (Lepidoptera: Saturniidae) (tropical Tasar) or by uni- to multivoltine species such as *Antheraea proylei* Jolly (Lepidoptera: Saturniidae) (temperate Tasar) that primarily feed the tender arjuna (*Terminalia arjuna* (Roxb.) (Combretaceae) and asan (*Terminalia tomentosa* W&A) (Combretaceae) leaves (Singh et al. 2001; Goel and Rao 2004; Jena et al. 2013). However, in commercial farming, arjuna leaves are allowed as primary food sources to *Antheraea* caterpillars (Ojha et al. 2009) for their higher survival and faster growth rate (Rath 2011). Therefore, the fast-budding *T. arjuna* plantations are more often cultivated in outdoor farming than the natural slow-growing *T. tomentosa*. However, the *T. arjuna* monoculture is highly vulnerable to pest assaults, especially by lepidopteran caterpillars and coleopteran grubs (Singh and Saratchandra 2002; Singh et al. 2004; Sasidharan and Varma 2008). Among the pests the most notorious and prevalent is the stem-boring 'lesser jewel beetle,' *Psiloptera fastuosa* (Fab.) (Coleoptera: Buprestidae) (Singh et al. 2001; Singh and Saratchandra 2002; Mandal and Das 2021). Most often the gravid beetles select the young arjuna stem for oviposition and development (Reddy et al. 1996; Mandal and Das 2021) which eventually causes permanent damage to the plant. Besides *P. fastuosa*, other buprestids, such as, *Sphenoptera barbarica* (Gmelin 1790); *Sternocera orientalis* (Mamalayya et al. 2019); and *Sternocera leavigata* Olivier (Mamalayya et al. 2019) are also reported to attack *Terminalia* plantations, but since they primarily breed and oviposit in *Shorea robusta* Roth (Dipterocarpaceae) and *Bassia latifolia* Roxb. (Sapotaceae), they are counted as secondary pests for *Terminalia* (Singh et al. 1985; Srivastava et al. 2012; Tirkey et al. 2019).

Adult *P. fastuosa* while attacking the *Terminalia* plantations creates twisting tunnels under the bark (Singh et al. 2001; Singh and Saratchandra 2002; Mandal and Das 2021); however, externally, the tunnels are seen as spiral ridges or cankers across the trunks. Usually, the gravid *P. fastuosa* oviposit eggs in clusters on arjuna bark crevices and after hatching, the neonate grubs chew and consume the vascular tissue inside the stem, grow and develop into pupae, metamorphose into adults, and emerge through distinct D-shaped emergence holes (2–3 cm width) by boring (Peterson et al. 2020). The young larvae generate extensive galleries along the stems' longitudinal axis, but older larvae engender in random transverse orientations, resulting in partial to total girdling (Schroeder and Eidmann 1993; Moraal and Hilszczanski 2000). During development, the flat-headed borer compacts its sawdust-like fine frasses into the tunnels which often causes gum exudation, bark cracking, and rotting of the stems (Tirkey et al. 2019). Generally, the number of emergence holes in a damaged plant may correlate with the plant's larval chambers (Turner and Hawkeswood 1996), and thus, the emerging holes can be linked to tree health and eventual wilting (Brown et al. 2017). With maturity, the larva penetrates deep into the tissue, causing significant scarring and impeding water and nutrient transfer (Brockerhoff et al. 2006), resulting in early defoliation (Evans et al. 2007; Muilenburg and Herms 2012), plant wilting and even death (Mendel et al. 2003). Therefore, recurrent *Psiloptera* attacks in arjuna has a long-term influence on survival and existence of *Antheraea* (Tirkey et al. 2019; Rath 2011). It is assumed that an increased presence of wood borer in the field causes increased plant wilting and eventual threat to the silkworm (Sallé 2016; Vega and Hofstetter 2014); whereas a decrease in available foliage hurts Tasar worm development and survival, leading to fewer and smaller cocoons and less silk production (Rath 2005; Jena et al. 2017).

Though it has been reported that such flat-headed, stem-boring buprestids may injure 22–40% of *Terminalia* plantations (Joshi 2012; Dhar et al. 1989), no comprehensive information on plant damage connected to the Tasar production economy is known. This is due to the fact that Tasar plantation health and management have been neglected in favour of the treatment and control of silkworm larvae. So far, no preventative methods have been devised to deal with the Tasar beetle, though it causes pandemics in Tasar farms. Furthermore, a lack of information about pest biology, modes of infestation, and control measures make it challenging to keep the Tasar plantation safe and sound. As a result, substantial research is needed to develop a better approach to reducing the plant's natural enemy to improve.

A. paphia generally habitats in outdoor Tasar farming. Given the prevalence of this annoying pest on arjuna hosts, the current study investigates the cause and consequences of *P. fastuosa* swarming behavior in outdoor *T. arjuna* plantations. Our primary research objectives include determining the seasonal fluctuations in *P. fastuosa* assaults on its primary host, as well as the kind and frequency of infestation on the host in a specific cultivated area. Furthermore, we examined if the age and dimensions of the host plant had an impact on the infestation of *P. fastuosa*. Finally, we attempt to assess the intensity of the pest infestation in arjuna plantation by measuring the emergence hole frequencies and wood gallery intensities of adult beetles. The objective of this study is to address the above inquiries in order to enhance the management and expansion of arjuna plantations for commercial Tasar culture.

Materials and methods

Location

The present study was conducted at three outdoor Tasar plantation farms (site I, site II, and site III) in Central India for 3 years (2017–2019). The study sites were located at Pali (22°22'N, 82°19'E) in Chhattisgarh, run under Central Tasar Research & Training Institute (CTRTI), India. Study site-I only had plants less than four years old (4 yr), study site-II had plants between four and eight years old (4–8 yr), and study site-III had plants older than eight years old (> 8 yr). The beetle's life cycle stages and infestation records were surveyed monthly for three years. Three equidistant (2 km ± 500 m) subplots, each measuring an area of nearly 450 m^2 (24.5 m × 18.5 m), were arbitrarily chosen from each study site. Thus, three subplots were selected from each site with known age of *T. arjuna* plantations. Since all plants were planted artificially, there was almost the same number of trees in each subplot (n = 300 ± 4). Plants were rowed in nearly equal grids, with a mean spacing of 1.2 m from row to column (Fig. 1). The study sites were surrounded by mixed deciduous degraded forests, and *T. arjuna* was the only tree in the subplots. Different study sites were chosen to compare beetle infestation between plant ages, and subplots were chosen to minimize unknown infestation bias. Mean temperature, humidity, and rainfall were recorded monthly throughout the survey.

Data collection

There were nearly 300 arjuna plants in a subplot, but only 30 were selected randomly for pest attack screening. Therefore, 90 plants (30 plants/subplot × 3 subplots) were chosen from a study site for continuous monitoring of beetle infestation. For comparable weighted calculation, the number of plants from a subplot (n = 30) and the total number of plants from all subplots of a site (n = 90) were kept constant. Therefore, a total of 270 plants (90 plants/site × 3 sites) were monitored for pest attacks. Plant monitoring has been carried out for three consecutive years (2017, 2018, and 2019). Therefore, 90 plants of the same age group (< 4 yr) were observed at study site-I, 90 plants (4–8 yr) were observed at study site II, and 90 plants (> 8 yr) were observed at study site III. During data

Fig. 1 Plant age and coleopteran beetle *P. fastuosa* infestation to Tasar (*T. arjuna*) farmland: **A** plants are < 4 year-old, **B** plants are 4–8 year-old, **C** plants are > 8 year old. **D** Adult emergence holes (marked with arrows) in an affected *T. arjuna* plant (inset: Vth instar grub of *P. fastuosa*). **E** Ribbon markings for affected plants in a study plot. **F** and **G** Partial to nearly complete demolition of *T. arjuna* plantation due to wilting (inset) caused by buprestid infestation

sampling, the plants were marked with different colored ribbons as per year to avoid overlapping data counts.

Pest infestation: emergence hole

The event of 'pest infestation' was demarcated by counting the emergence holes caused by the adult beetles on the surface of the plant stem (Thiemann et al. 2016), as the larval chamber in the plant can be linked with the number of emergence holes (Turner & Hawkeswood 1996). Using a hand magnifying lens and a binocular, the number of emergence holes was counted as accurately as possible in standing and falling trees. Emergence holes were counted for each plant age group (< 4 yr/4–8 yr/ > 8 yr) for each year. During counting, the emergence-hole distances (cm) from the ground (emergence-hole height) were measured with a measuring tape and a laser distance-meter (Bosch GLM-40) as applicable. In addition, the length (cm) of each selected plant was measured using a forest clinometer (Nikon) as described by Larjavaara and Muller-Landau (2013). Emergence holes recorded in 2017 from site-I (4-year old plantations only) were labeled with a permanent fluorescent dye (Nelson, India); if any emergence hole was found during 2018, it was counted and marked with a second colour; and likewise, if any emergence hole appeared during 2019, it was again counted and marked with a third colour to avoid duplicate records. Likewise, emergence holes from sites II (4–8 years) and III (> 8 years) were counted and marked year by year. The pest infestation percentage was determined using the following formula:

(Affected plants = the presence of any emergence hole in the plant's main trunk or branches)

Pest infestation percentages were estimated independently for each plant age group by year; the distributions of emergence holes on the main trunk (up to the fourth node) and lateral branches (up to the second node) were also recorded independently. Furthermore, the diameter (mm) of each damaged plant at its thickest end was recorded according to plant age.

Pest infestation: wood gallery

We randomly collected five stems of varying lengths of *T. arjuna* trees showing *P. fastuosa* borer symptoms for each subplot and stored them in rearing cabinets until adult emergence. Affected stems were trimmed from the ground up to 20 cm above the uppermost emergence-hole mark. Thus, 15 damaged stems were collected from each plant age group, totaling 45 from all study sites. Stems were sliced for longer logs and huddled for storage in cabinets. At adult emergence, barks were removed from the stems to estimate gallery formation and gallery coverage following methods described by Ryall et al. (2011). Stems were cut transversely at their thickest end and vertically in the center to estimate gallery coverage. By laying a thread on the scars and using a digital caliper (Freemans U.K.), the overall length and branching of the borer's journey path (gallery length and gallery depth, mm) were measured, considering the thread length. Gallery length and depth were measured independently for each plant age group at the end of each year (November–December).

Pest infestation: plant wilting

The number of wilted plants from each plant-age group (< 4 yr; 4–8 yr; > 8 yr) was counted at each study site. The percentage of wilted plants was calculated based on the number of plants wilted out of the total observed plants for a given plant-age group (n = 90). For wilting counts, only those damaged plants with partially broken (bending end did not touch the ground) or entirely broken main trunks (bending end touched the ground) were counted; however, we did not count any bowed branches other than the main trunk. Wilting counts were recorded annually and aggregated for each plant age group after three years. Next, we counted the number of emergence holes in each plant-age group from each wilted plant. The total number of emergence holes in that year and all prior years are added and compared to plant wilting for a given plant-age group.

Pest occurrence: life stage

P. fastuosa, life stage samples, were collected month-wise from each study site by hand / forceps-picking (for eggs), net-sweeping / light-trapping (for adults), and wood-excavating (for pupae and grubs) according to availability following methods described by Ryall (2015) and Francese et al. (2008). All samples were classified into life stages and stored individually in containers labeled with the collection month. The samples were taken to the laboratory for identification, tabulation, and analysis. We dissected at least five wilted stem sections of a variable for each subplot size per month to collect grubs and pupae. All life stages (egg, grub, pupa, and adult), living or dead, observed in a given month were documented. Data from three study sites were pooled together for a month to determine the occurrence percentage for each life stage. The proportion of occurrences of a life stage was computed monthly by taking the total numbers for the month.

Data compilation and analysis

A maximum-minimum transformation method was employed to normalize the data. Normality was tested in each case, and the findings were recorded in the result section. The Shapiro–Wilk test was performed to determine whether or not the data were normally distributed. Non-parametric statistical analysis was conducted throughout to analyze the data of 'pest infestation' (emergence holes). We also correlate among gallery distance (mm), plant width (mm) and gallery depth (mm). Kruskal–Wallis test was used to compare plant age and emergence holes, and finally, variations in plant emergence holes were analyzed using Dunn's test. In order to examine the variations in field infestation of the beetle, the normality of the data was assessed. The Shapiro–Wilk test indicates that there is a considerable deviation from normality in terms of pest infestation among the three subplots (W = 0.758, p < 0.05). Therefore, non-parametric tests were conducted to compare infestations for independent sites. In addition, a Shapiro–Wilk test was used to assess the normality of the data in order to compare the number of emergence holes per plant across different age groups of plants. Due to the lack of normality in the results (W = 0.852, p < 0.05), non-parametric tests were conducted again. Similarly, in order to examine if plant width is a determining factor for pest infection, the normality of the data was assessed using the Shapiro–Wilk test. The results indicate that the data for plants with a diameter of 3 cm followed a normal distribution (W = 0.967, p = 0.876). However, the data for plants with diameters of 3–6 cm (W = 0.848, p < 0.05) and > 6 cm (W = 0.912, p < 0.05) did not exhibit normality. Therefore, non-parametric statistics were used once again.

Result

Pest infestation

Infestation variation in field

Since Krukal-Wallis test showed no significant difference in pest infestation among the three subplots for a certain aged plant (Site 1: $\chi^2_{(2,8)} = 0.26667$, $p > 0.05$; Site 2: $\chi^2_{(2,8)} = 4.62222$, $p > 0.05$; Site 3: $\chi^2_{(2,8)} = 4.62222$, $p > 0.05$), we combined the data and compared the result by study site. There was no significant difference of pest infestation across the three sub-plots from a study site.

While analyzing pest infestation for a specific plant age-group (from all subplots of a given study site), there was also no significant difference in pest infestations from one year to the next over the three studied years (2017, 2018, and 2019) at any of the three study sites (Site I, 4 yr: $\chi^2_{(2,8)} = 7.2$, $p > 0.05$; Site II, 4–8 yr: $\chi^2_{(2,8)} = 3.2$, $p > 0.05$; and, Site III, > 8 yr: $\chi^2_{(2,8)} = 3.2$, $p > 0.05$) (Fig. 2). The findings reveal that the beetle invasion has followed a consistent trend throughout the studied years.

Age-dependent plant damage

Among 270 plants from three study sites (90 plants × 3 sites), the mean damaged plant for the first (2017), second (2018), and third (2019) years were minimum (5.66 ± 1.88%, 4.80 ± 0.89%, and 5.45 ± 1.89%, respectively)

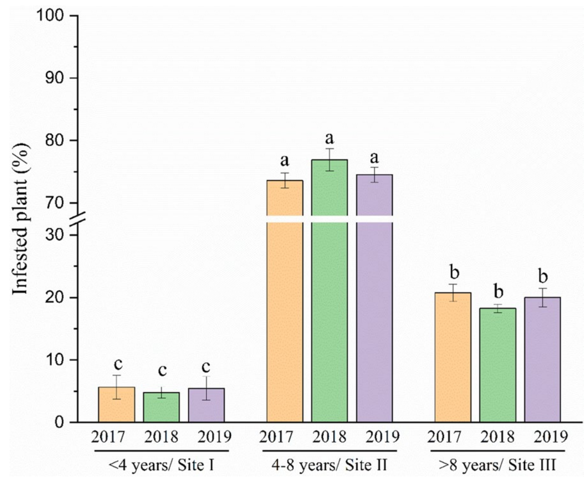

Fig. 2 The wood borer *P. fastuosa* infestation to *T. arjuna* plantations according to plant age (< 4 years; 4–8 years; > 8 years) and year of attack (2017; 2018; 2019). Pest infestation varied significantly with plant age ($\chi^2_{(2,27)} = 23.14286$, $p < 0.05$) (indicated by letters 'a', 'b', and 'c' according to the Dunn test). Pest infestation in particular aged plants does not vary significantly from year to year (indicated by the same letters; < 4 years: 'c', 'c', 'c'; 4–8 years: 'a', 'a', 'a'; > 8 years: 'b', 'b', 'b')

for younger trees (< 4-yr). Moderate-aged plants (4–8-yr) had a higher infestation rate (2017: 73.58 ± 1.20%; 2018: 76.92 ± 1.78%; 2018: 74.54 ± 1.20%), whereas in advance-aged plants (> 8 yr), infestation rates were moderate (2017: 20.75 ± 1.40%; 2018: 18.26 ± 0.67% and 2019: 20.001.50%). However, among the examined sites, the mean infestation percentages as per plant age groups were: < 4 yr: 5.30 ± 0.36%, 4–8 yr: 75.02 ± 1.4%, and > 8 yr: 19.67 ± 1.04%, respectively. The results reveal that 4–8-year-old plants are more pest-prone (75%) than younger (5%) or older (19%) trees.

Although pest infestations were not statistically different in subsequent years for a specific aged plant group, a significant variation in infestation was identified among plant age groups ($\chi^2_{(2,8)} = 7.2$, $p < 0.05$). This information indicates that buprestid infestation in arjuna is plant-age dependent (Fig. 3). Subplot-wise pest infestations within site, as well as year-wise pest infestations within a plant-age group, were found to be statistically non-significant, but when data were compared between plant-age groups (across sites), a significant record of pest infestation ($\chi^2_{(2,27)} = 23.14286$, $p < 0.05$) was observed (Fig. 2).

Pest infestation as a function of plant age

The signs of emergence holes from plants are indicative of pest infestations, and their number from different plant ages varied greatly. There was a significant difference in the number of emergence holes across all plant age groups ($\chi^2_{(2,240)} = 26.50675$, $p < 0.05$).

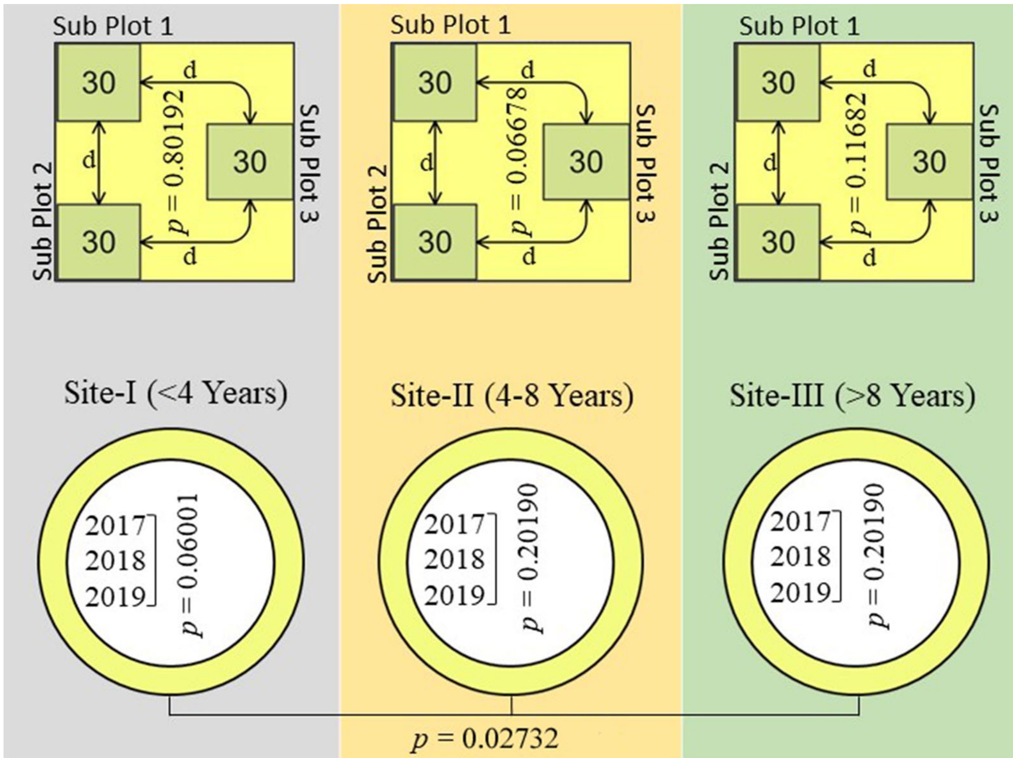

Fig. 3 Schematic representation of *P. fastuosa* infestation to Tasar plants. Each column represents the experimental sites (Site I covering 4-year-old plants; Site II: 4–8; Site III: > 8) from where three equidistant equal-sized subplots with an equal number of plants (n = 30) were surveyed for three consecutive years (2017 to 2019). Subplot-wise pest infestations within a site, and year-wise pest infestations within a plant-age group were found to be statistically non-significant; however, when the data were compared between plant-age groups (among the sites), a significant result of pest infestation ($p = 0.02732$) was observed

However, Dunn's test analysis shows that there is no significant difference in emergence holes between 4-year and 4–8-year-old plants ($p = 1 > 0.05$) or between 4-year and > 8-year-old plants ($p > 0.05$). However, there was a significant difference in the number of emergence holes between 4 and 8-year-old and > 8-year-old plants ($p = < 0.05$) (Fig. 4). For this analysis, we have disregarded the differences between the three years (2017, 2018, and 2019) and only considered three age groups (> 4 years, 4–8 year and < 8 years).

Pest infestation as a function of plant height

The relative positions of emergence holes in affected plants vary with plant height. While analyzing the relative positions of emergence holes in affected plants, it was observed that 38.49% of emergence holes were distributed at around 1/4 of the plant height (H) from the ground (H-1/4); 45.06% of emergence holes were distributed at 2/4 of the plant height above H-1/4 (H-2/4); 7.35% of emergence holes were distributed at 3/4 of the plant height above H-2/4 (H-3/4); and 9.09% of emergence holes were distributed at the rest of the plant height above H-3/4 (H-4/4). With respect to increasing plant height, the level of lowermost and uppermost emergence holes from the ground also increases. As a result, there was a positive correlation between plant height and either the height of the lowermost emergence hole (Pearson's r = 0.70489) or the height of the uppermost emergence hole (Pearson's r = 0.85522). However, correlation between the total number of emergence holes for a plant to its height showed a weak relationship (Pearson's r = 0.15375) (Fig. 5). Therefore, it can be concluded that as height increases in the plant, the number of emergence holes remains constant, but the distance of emergence holes from ground increases significantly with age.

Pest infestation as a function of plant width and side branching

To determine any association between the width of a plant and the occurrence of pest infestation, we measure the number of infestations in plants of varying widths. It was observed that plants with bigger diameter were affected less than slender trees, regardless of plant age (correlation, ρ = -0.0471). In quantification of emergence holes to plant width, it was observed that plants with < 3 cm diameter had a mean emergence hole of

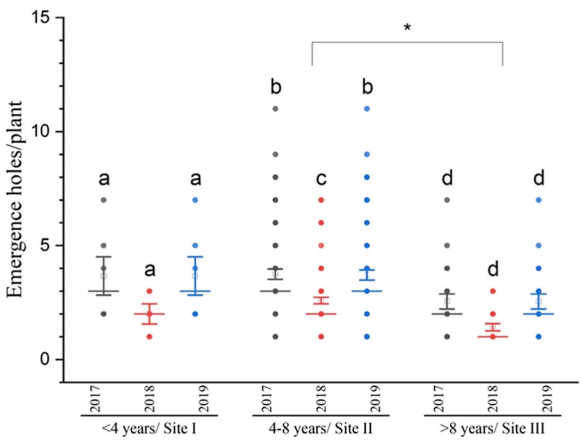

Fig. 4 Adult emergence holes (EH) of coleopteran pest, *P. fastuosa* from *T. arjuna* according to plant age and year of attack. The number of EHs/plant significantly correlated with plant age ($\chi^2_{(2,8)} = 26.50675$, $p < 0.05$). The number of EHs for 4–8-year-old plants significantly varied with advance aged plants (> 8 year) ($p < 0.05$). Data analyzed based on observations of exclusive EHs for the year; the number of EHs in a given year was not combined with the number of EHs in the preceding year. Kruskal-Walli's test was performed followed by Dunn's test to check any significant difference of EHs among three study sites in three consecutive years. Similar letters ('a', 'a' or 'b', 'b' or 'c', 'c' or 'd', 'd') indicate there was no significant difference (Dunn's test), but the different letters ('a', 'b', 'c', 'd') indicate there was a significant difference (Dunn's test) of data. Within the three sites, separate Kruskal-Walli tests were performed, followed by Dunn's tests. Within site, 'a,' 'b', 'c', or 'd' marking was used to compare emergence holes per plant recorded in three consecutive years, 2017, 2018, and 2019

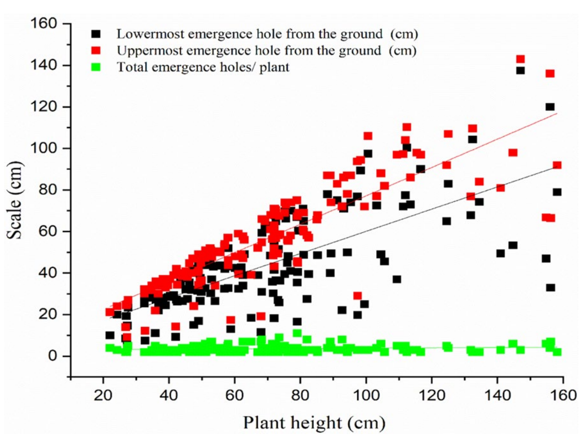

Fig. 5 Distribution of lowermost and uppermost emergence holes of the affected *T. arjuna* plants according to plant height (cm). A moderate to strong positive correlation exists for lowermost (black dots) (Pearson's r = 0.70489), and uppermost (red dots) (Pearson's r = 0.85522) emergence holes with plant heights (X-axis). Total number of emergence holes/plant, however, showed weak correlation (green dots) (Pearson's r = 0.15375) with plant height

3.57 ± 1.99; plants ranging in diameter from 3 to 6 cm had 3.24 ± 1.84 emergence holes, whereas plants with > 6 cm diameter had 3.07 ± 1.62 emergence holes (Fig. 6). There was no significant difference between the width variation of the host plants and the number of emergence holes.

Pest infestation as a function of gallery formation

The mean gallery length (end-to-end distance) in arjuna generated by the beetle was 62.97 ± 5.06 mm, irrespective of plant age. The mean penetration of the borer inside the stem from the bark surface (gallery depth) was 7.44 ± 0.84 mm for any plant age. After considering the length and depth of the galleries, this investigation reveals that the extent of *P. fastuosa* attacks on arjuna is depends to the age of the plant. The correlation coefficients between the mean plant diameter (plant width) and gallery distance (correlation, ρ = 0.21) and gallery depth (correlation, ρ = 0.05) (Fig. 7) indicate that gallery formation by the beetle is associated with the width of the host plants. The positive correlation coefficients between plant width and gallery distance show a direct relationship between these variables. A tree with a larger diameter will have a greater gallery distance.

Plant age, emergence holes, and wilting

Wilting in *T. arjuna* plantations caused by *P. fastuosa* infestation varied greatly with plant age. Only 5% of wiltlings were recorded in younger (< 4 years) plants with an average of 3 ± 1 emergence holes. However, wilting reached to maximum (78%) in 4–8-year-old trees with an average of 4 ± 1 emergence holes. Wilting drops

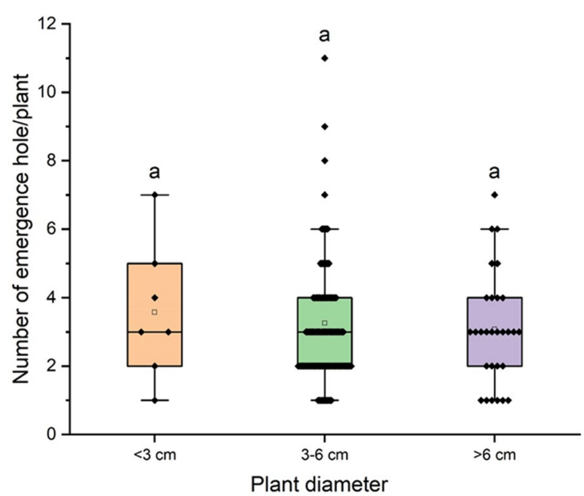

Fig. 6 Emergence hole(s) per plant according to plant girths. A non-significant difference ($\chi^2_{(df=2)} = 0.38128$, $p < 0.05$) of emergence holes was recorded in different diameters (< 3 cm, 3–6 cm, > 6 cm) of host plant widths

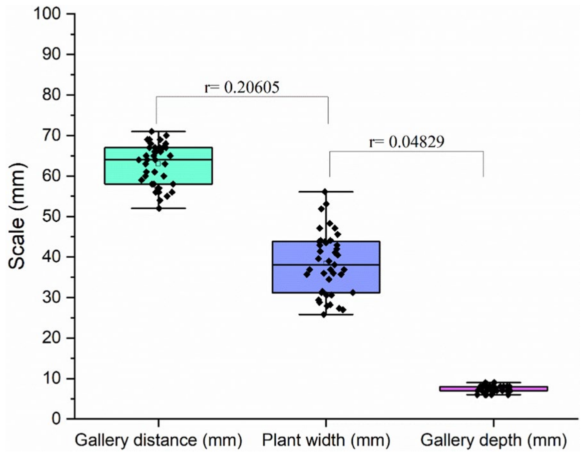

Fig. 7 Gallery distance and depth caused by coleopteran wood borer, *P. fastuosa* in *T. arjuna* stem. Significant correlations exist between plant width (mm) to gallery distance (mm) (Correlation = 0.21), and plant width (mm) to gallery depth (mm) (Correlation = 0.05). Each box, along with the corresponding scattered dots (specified for a particular holes) indicates the magnitude of data (designated by upper and lower quartile numeric values with a median dot)

noticeably to 17% in relatively older plants (> 8 years) with an average of 4 ± 2 emergence holes per plant (Fig. 8).

Life stage and pest infestation

According to our findings, the pest *P. fastuosa* completes its life cycle in the wild for nearly the entire year. Adults were primarily seen in the field from the September equinox to the December solstice (mean temperature 19.97 °C; RH 51.68%) when gravid females oviposit. The egg hatched between October and November at 25 °C and 70% R.H. The hatchlings (grubs) passed through five instar stages and reached maturity by summer (June solstice to September equinox) (mean temperature 38.5 °C; R.H. 76%) (Fig. 9). *P. fastuosa* primarily infests *T. arjuna* plantation throughout pre-winter and winter (December solstice to March equinox). Most plant wilting was noticed during the monsoon (June to July).

Discussion

Our findings on *P. fastuosa* infestations of arjuna reveal that plants aged four to eight years are more prone to pest attacks. Younger trees (less than four years old) and older trees (eight years or older) were less susceptible to pest infestation. These data imply that the host plant's age directly impacts buprestid invasion. It may be due to the

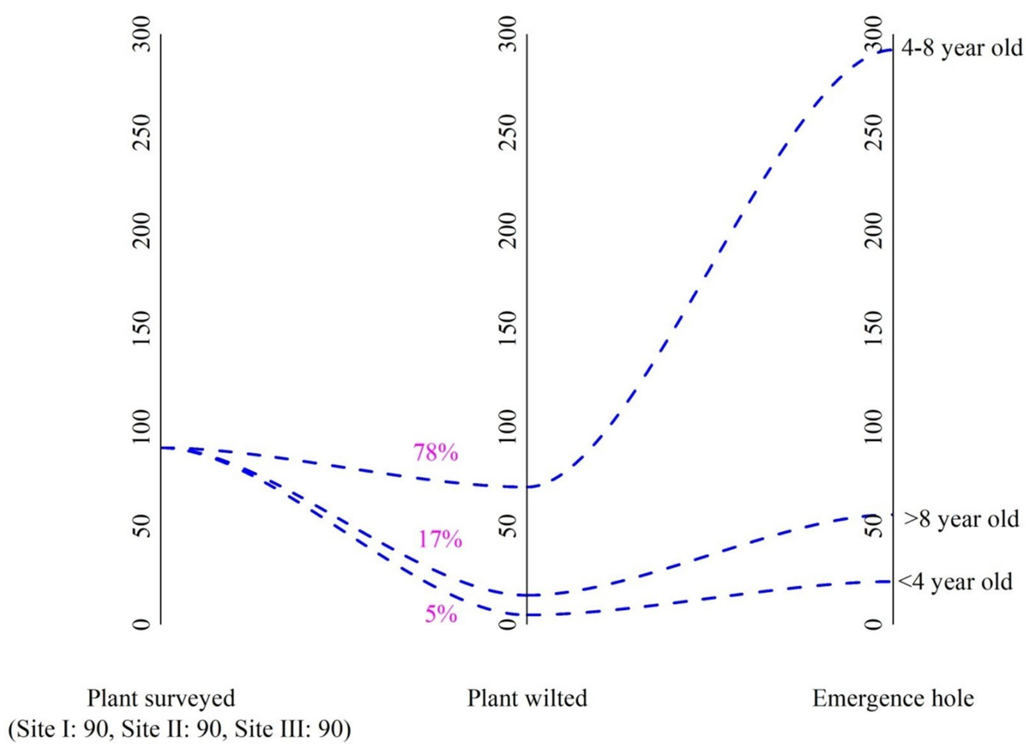

Fig. 8 Incidence of host-plant (*T. arjuna*) wilting according to plant age and number of emergence holes (EH) in arjuna. Only 5% wilting recorded in < 4 year old plants (EH: 3 ± 1 per wilted plant), 78% wilting in 4–8 year old plants (EH: 4 ± 1 per wilted plant), and 17% wilting in > 8 year old plants (EH: 4 ± 2 per wilted plant). The number of EHs of a plant for a given age is shown as the sum of the aggregate number of EHs of the year and all the previous years of that plant. The relation of plant wilting to EHs is established

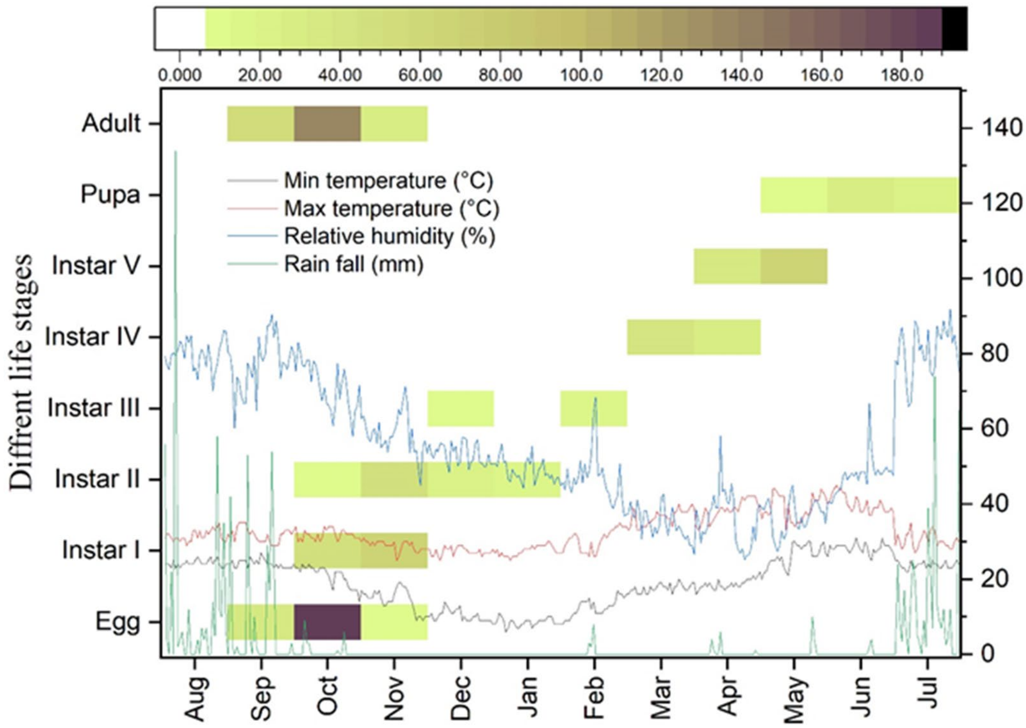

Fig. 9 Life cycle stages of *P. fastuosa* in field condition. The colour scale (top bar) indicates occurrence percentage of different life stages of the beetle. The temperature, relative humidity (RH) and rain fall scales are reflected in Z-axis

absence of heartwood in four- to eight-year-old plants, as grubs prefer soft, fragile woods over older, more mature trees. However, younger plants under four years old were not susceptible to assault by buprestids since they had not yet developed any woody compounds. Evidence from adult emergence holes in *T. arjuna* suggests that host plant age is the most critical factor in ensuring the long-term viability of Tasar tree plantations in the wild. The number of emergence holes (infestation signs) and the age of the host plant were to have a direct relationship. We can rule out the possibility that the differences in infestations are related to differences in population levels between the locations because we found no significant differences in pest infestations among the subplots of a certain age of plants. Again, pest infestations were non-significantly different in site-restricted subplots over the examined years for a specific plant age group, showing that buprestids infested the Tasar crop plants at nearly the same rate throughout the study period.

When the affinity of insect infestation was analyzed to plant length, it was found that the rate of pest infestation was inversely related to plant height. This means that the number of pest attacks decreases as the plant length increases from the ground. The majority of the infestation signs were detected in the first half of the tree trunks, demonstrating *P. fastuosa's* propensity for oviposition close to the ground. *T. arjuna's* main stems were more vulnerable to beetle attack than its branches. Infestation symptoms were reported to be more common in slender plants than in robust ones. However, statistical analysis revealed that the girth of the trees had no effect on pest infestation, though gallery intensities were correlated with plant widths. Our data suggests that the beetle usually predominately attacks 4–8 yr old arjuna with a diameter of 3–6 cm. However, this data appears to contradict the age-dependent plant infestation. However, we found no evidence of infestation inclination to change plant widths in 4–8-year-old plants. This finding suggests that the beetle can infest plants of any diameter between 4 and 8 years. Furthermore, the severity of the grubs' wood galleries was varied to the age and width of the trees. Since young stems are more attractive to herbivorous insects than older stems of the same species as they have more resource exploitation potential, plant age can be directly linked to the intrinsic resistance to herbivore attacks, and thus, the relationship between pest attack and plant age can be treated as an independent event (Kearsley and Whitham 1989; Patil et al. 2016).

Plants between the ages of 4 and 8 years were more wilted than younger or older plants. Wilting was observed at only 5% for younger (<4 yr) plants, but it reached a high (78%) in intermediate-aged

(4–8 yr) plants; nevertheless, wilting decreased drastically (17%) in older (> 8 yr) plants. Given that the average number of emergence holes in wilted plants of moderately-aged (4–8-yr) and older (> 8-yr) plants was nearly similar, it is plausible to conclude that plant age, despite being represented by an equal number of emergence holes, is a determinant of the wilting event (infestation). A plant that is 4–8 years old is more prone to wilting than its older population. Even though the emergence holes per wilted plant for > 8-year plants were nearly the same as for 4–8 year plants, they may not have wilted as frequently, possibly due to greater lignifications in its woody tissues.

Temperature and moisture are essential factors in an insect's lifecycle, and these two conditions appear to regulate the presence of buprestid beetles in the wild (Prasad and Logiswan 1997; Duan et al. 2010; Holynski 2019). Adult beetles oviposit their eggs individually or in small clusters into the bark ridges of *T. arjuna* throughout autumn (September equinox to December solstice), and once the eggs hatch, they penetrate inside the stem in a safe and protected area, and it makes it difficult to control them. Therefore, the autumn season provides a clear indicator of their Control before entering the stem. In conclusion, insecticidal sprays on Tasar cropland during autumn around the mid-region of the 4–8-year-old affected *T. arjuna's* main trunks are recommended for controlling the buprestid pest, *P. fastuosa*.

It has been reported that besides *Psiloptera fastuosa*, another flat-headed stem borer, *Sphenoptera konbierensis* also infest *T. arjuna* and *T. tomentosa* severely (Dhar et al. 1989). Besides Tasar plantations, several *Psiloptera* also cause severe damage to gum-producing trees like *Acacia senegal* (hasbab) and *Acacia seyal* (talh) in Africa (Jamel 1994) where oriental *Psiloptera orientalis* damages severely the lack Plum, *Syzygium cumini* (L.) (Kakulte and Mamlayya 2022). Though certain flat-headed stem boring buprestid species may harm 22–40% of *Terminalia* plantations depending on field location (Joshi 2012; Dhar et al. 1989), there is no complete information available on plant damage and the production economy of Tasar. While attacking *T. arjuna* by other bark-eating borers such as *Aeolesthes holocericea* (Fab.) (Coleoptera: Cerambycidae) (Sinha & Sinha 2012), *Inderbela quadrinotata* (Walk) (Lepidoptera: Cossidae) (Mathew & Rugmini 1997), and *Sphenoptera cupriventris* (Kerr) (Coleoptera: Buprestidae) (Reddy et al. 1996) it has been reported that the borers can be controlled by using chlorpyrifos (organophosphate) (20% effective concentration, E.C.; 80–88% reduction in infestation), dichlorvos (organophosphate) 76% E.C.; 59–62% reduction in infestation) and Azadirachtin (neem extract) (10,000 EC; 57–58% reduction in infestation) (Kamble & Sathe 2022). However, there is no information available on the use of insecticides to manage *P. fastuosa*. Although we have seen that organophosphate pesticides effectively control *P. fastuosa*, more research on pesticide kind and dose for controlling *P. fastuosa* is needed.

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Author contributions
Das conceptualized the idea, and S.M. and KCM designed the experiments. S.M. conducted sample collection and all experiments along with KCM. S.M., A. Dolai analyzed the data. All graphical illustrations were prepared by A. Dolai. S.M. drafted the manuscript initially; A. Das revised the draft finally.

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