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Do floral traits and rewards effects floral visitation in Syzygium parameswaranii; An Endangered evergreen tree of the southern Western Ghats of India?

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Research Article

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Posted Date: October 25th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-5308465/v1

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Do floral traits and rewards effects floral visitation in *Syzygium parameswaranii*; An Endangered evergreen tree of the southern Western Ghats of India?

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Abstract

Syzygium parameswaranii is a mass-blooming endangered tree species endemic to the Western Ghats of India. The reproductive phenoevents of *S. parameswaranii* were significantly correlated with temperature which indicated that the flowering phenoevents should be accelerated by a specific temperature. Due to its poor floral rewards (nectar) and advertisement, a limited number of floral visitors were drawn to the blossoms of *S. parameswaranii*. Since there were no attractive or colourful sepals or petals, the large number of stamens served as the major floral attractant and provided pollen grains as a major floral reward because the quantity of nectar was very low. The diversity of floral visitors in *S. parameswaranii* was relatively limited when compared to other species of *Syzygium*. The flowers were attracted and visited by only twelve species including ants, bees, beetles, butterflies, moths and wasps. Among these visitors, only seven of them served as efficient pollinators. *Scolia dubia* was recorded with higher visitation frequency (0.78±0.11) and visitor activity index (0.89) than any other visitor. Due to their frequent visits and effective stigma contact, they were recorded as the most effective pollinators of *S. parameswaranii*.

Keywords: Myrtaceae; Shannon-Weiner inde;x Visitation rate index; Visitor activity index; pollination efficiency

Introduction

The genus *Syzygium* Gaertner is one of the most extensive plant groups within the Myrtaceae family, comprising around 1200 species (Parnell *et al*., 2007; Govaerts *et al*., 2020; POWO, 2023). They are mainly concentrated throughout Southern and South East Asia, as

well as in Southern China, Malaysia, Australia and New Caledonia. Some of the species were reported from Africa, the Mascarene Islands, Hawaii, Malagasy, New Zealand, and the Pacific Islands (Parnell *et al*., 2007). So far about 102 species of *Syzygium* have been documented in India with 54 of these species being found in the Western Ghats of India (Anjana, 2020). Of these, 28 species are reported as endemic (Shareef and Santhosh Kumar, 2020). Globally, 77 species of *Syzygium* are recorded as Critically Endangered, 109 are Endangered, 76 are Vulnerable and 20 are included in the near-threatened category of the IUCN Red List (IUCN, 2022-2). *Syzygium parameswaranii* is an endangered and endemic species of the few localities within the Agasthyamalai Biosphere Reserve and Megamalai Wildlife Sanctuary in the Southern Western Ghats of India. Because of the rapid decline in population and inadequate conservation approaches, this tree species has been included in the Endangered (B1+2c ver 2.3) category of the IUCN Red List (IUCN, 2023-1). This tree species also holds great ecological significance as they provide food and habitat for numerous organisms including floral visitors, frugivores and seed dispersers. The fruits of *S. parameswaranii* are consumable and are ingested by endemic primates, birds, rodents, and a variety of insects (Athira, 2023; Athira and Ramasubbu, 2023).

Plant-pollinator interactions are the extensively studied aspect of reproductive ecology in angiosperms. It involves the mutualistic response mechanism between plants and pollinators; pollinators act as pollen vectors and in return, plants provide food for pollinators (Nicolson and Wright, 2017). Flowering plants employ advertising tactics to attract and retain floral visitors, thereby facilitating pollination. The advertisements include various factors such as distinctive shapes, sizes and attractive colours exhibited by flowers and the enchanting presence of floral scents. They also entice pollinators by offering floral rewards such as nectar and pollen grains to maintain and ensure successful pollination (Shivanna and Tandon, 2014; Wester and Lunau, 2017; Koski, 2020; Essenberg, 2021). The degree to which flower visitors serve as selective agents of floral traits is determined by their effectiveness as pollinators (Fumero-Caban and Melendez-Ackerman, 2007). Climate change has remarkable impacts on the phenology, abundance and distribution of both plants and pollinators (Hegland *et al*., 2009). Anthropogenic influences such as climate change, habitat loss, fragmentation, use of pesticides, exotic species and pathogens are causing a reduction in the diversity and abundance of wild pollinators, which in turn affect their significant contribution to crop yield (Kennedy *et al*., 2013; Garibaldi *et al*., 2014; Potts *et al*., 2014).

Endemic species are commonly more susceptible to human-induced threats and natural changes and face a severe risk of extinction (Coelho *et al*., 2020). So, the conservation of these

species become a major concern. The survival of species and its associated biodiversity is dependent on successful reproduction and further regeneration. So, studies on the reproductive ecology of trees are essential for the conservation and management of biodiversity (Shivanna and Tandon, 2014). The reproductive inefficiency of *S. parameswaranii* was reported mainly due to the phytophagous wasp, *Anselmella kerrichi*. These wasps have oviposited their eggs into the hypanthium of flowers, causing adverse effects on fruit formation and seed set (Athira and Ramasubbu, 2020). The populations of *S. parameswaranii* are in severely disturbed areas within the commercial plantations of tea, coffee and cardamom (Athira and Ramasubbu, 2020). So, further studies need to find out whether the tree species experiences any other constraints related to reproduction, especially in pollination. Because, the use of anthropogenic chemicals such as pesticides, herbicides and fungicides will directly or indirectly affect the activity of pollinating insects (Mullin, 2015; Sponsler *et al*., 2019). Despite its endemic and endangered status, the reproduction of *S. parameswaranii* remains poorly studied. This study aims to investigate how floral traits contribute to the attraction of floral visitors. The major objective of the current study is to examine whether the floral traits and rewards are adequate for successful reproduction in *S. parameswaranii*. Surprisingly, no studies have been undertaken to investigate its phenology, floral biology and pollination ecology, leaving a significant knowledge gap in our understanding of the species. Therefore, the primary goal of this study was to investigate the floral morphology, floral attractants and rewards and the pollination ecology of *S. parameswaranii*.

Study Area

The study was carried out within the Megamalai Wildlife Sanctuary situated in the Theni district of Tamil Nadu, India. This protected area is combined with Srivilliputhur Grizzled Squirrel Sanctuary and declared as Srivilliputhur-Megamalai Tiger Reserve in 2021 by the Government of India (Aravind, 2021). Megamalai Wildlife Sanctuary lies at an altitude range of 1550 -1700 m and between 9º40.941' N-9º41.243' N latitude and 77º22.866 E-77º27.275 E longitude (Athira *et al*., 2022) and spread over 269.10815 km^2 (National Wildlife Database, 2020). This region serves as a transitional area between the Periyar Tiger Reserve in Kerala and Srivilliputhur Grizzled Squirrel Sanctuary in Tamil Nadu. The Megamalai Wildlife Sanctuary consists of a variety of vegetation types such as tropical dry deciduous forest, tropical evergreen forest, open rock with grass, montane shola grasslands, tropical moist deciduous forest and riverine forest (Bhupathy *et al*., 2012). Megamalai hills otherwise known as the High Wavy mountains and the rivers Vaigai, Vaipar and Sruliar have their catchment area in this region. The dense montane rainforests of this region was severely replaced by

plantations of cardamom, coffee and tea (Ganesh *et al*., 2014; Athira *et al*., 2022). The Megamalai Wildlife Sanctuary experiences a mean temperature ranging from 11.66-29.14℃, along with a relative humidity between 78.54-89.95%. The wind speed of the Sanctuary recorded varies from 16.21 km/h to 26.13 km/h and the rainfall ranges from 2.39 to 10.4 cm (Selvarani *et al*., 2015).

Materials and Methods

Phenology

The vegetative phenophases such as leaf emergence, maturation and leaf shedding of selected individuals (n=25) were monitored. The reproductive phenoevents such as initiation and maturation of floral buds, the commencement of flowering and fruit development, ripening and dispersal of fruits and germination of seeds were recorded. About twenty-five mature individuals were randomly chosen and tagged from various populations for the assessment of phenoevents. The flowering phenological characteristics such as commencement, peak, and end of flowering were observed at respective phenoperiod. Mature flower buds (N = 25) were marked from randomly seelcted individuals (N = 25) to investigate the floral phenological characteristics like flower opening, anther dehiscence, and lifespan of flowers (Shivanna and Tandon, 2014; Athira et al., 2022).

Impact of climatic variables on flower and fruit induction

The impact of climatic variables on the phenoevents of *S. parameswaranii* was studied for three consecutive years (2019, 2020 & 2021). The mean monthly rainfall and temperature data were collected from the AccuWeather forecast (https://www.accuweather.com) for the study period. The vegetative phenoevents were analyzed qualitatively by direct observation, from which the presence or absence of phenoevents was recorded. The phenological events were evaluated using phenoevent scores such as 0 (no phenoevent), 1 (low), 2 (moderate), and 3 (significant) (Broadhead *et al*., 2003; Nadarajan and Pujari, 2019).

Statistical analysis

All the collected data were analysed by the Shapiro-Wilk test to check the nature of their distribution (normal or not). Due to the normal distribution of the data, Pearson correlation was performed to find out the relationship between reproductive phenoevents such as flowering and fruiting with climatic variables (temperature and precipitation) for the three years (2019-2021). The correlation graphs were generated using the Corrplot package (Version 0.92) (Wei and Simko, 2017). The statistical software R version 4.1.0 was employed to conduct all these analyses (R Core Team, 2021).

Flowering and fruiting intensity

The intensity of flowering and fruiting was assessed using the semi-quantitative method introduced by Fournier (1974), which was categorized into five classes from 0 to 4, each with a 25% interval between classes.

$$\% \text{ Fournier} = \frac{\sum \text{Fournier}}{4N} \times 100$$

Where, $\sum$ Fournier denotes the sum of Fournier classes of each individual and N represents the total number of individuals (Boas *et al*., 2013; Araujo and Lobo, 2020).

Morphology of floral parts and floral rewards

The floral morphological features of *S. parameswaranii* were analyzed by dissecting randomly chosen freshly opened flowers (N = 25) from the sample population under different microscopes (Leica EZ4W microscope and Celestron Handheld digital microscope PRO). The dimensions of floral parts including hypanthium, petals, style, ovary, and filament were measured with a measuring scale and a digital Vernier caliper (Aerospace digital 0-300 mm). The number of units within each floral whorl, the size of the flowers and individual floral units were also calculated.

A total of twenty-five unopened blossoms with undehisced anthers were selected to analyse the pollen productivity. The method proposed by Shivanna and Tandon (2014) was employed to quantify the pollen grains produced per flower. Mature and unopened anthers were collected and then crushed into a solution of 1-5 ml of sucrose/glycerine solution or water with a drop of detergent solution. The anthers were gently mashed to release the pollen grains with the help of a glass rod. Following this, 100µl of pollen solution was transferred into a clean hemocytometer, where the mean number of pollen grains was calculated. The total number of ovules per flower was assessed using a dissection microscope. The pollen-ovule ratio was computed by dividing the average number of pollen grains per flower by the average number of ovules per flower (Cruden, 1977). Stigmas (N = 25) at different development stages were selected to evaluate receptivity at various intervals from the day before anthesis to the seventh day after anthesis. A droplet of hydrogen peroxide solution was placed directly on the stigma and inspected for bubble formation (Kearns and Inouye, 1993) to check stigma receptivity.

The mature floral buds (N = 25) were randomly selected and bagged before anthesis to avoid floral visitors. On the day of anthesis, the bags were removed and nectar was measured by inserting a calibrated capillary tube into the bottom of the flower. To estimate the volume of nectar, the capillary tube's length in which the nectar translocated was measured to the point of calibration. Furthermore, a portable refractometer (Erma RHB-32 ATC) was utilized to determine the nectar concentration at various flowering stages. The refractometer readings

reflect the concentration of nectar as a percentage of sucrose equivalents (Dafni, 2005; Shivanna and Tandon, 2014).

Floral visitors and their visiting behaviour

The diversity of floral visitors foraging the flowers of *S. parameswaranii* was observed during the flowering period in general and peak flowering in particular from 06:00 h to 18:00 h. The visitation by diurnal visitors was persistently documented throughout the blooming periods for the entire observation time of 12 hrs/day. Studies on flower visitors and their foraging nature were examined through visual observation and with the aid of binoculars. The number of floral visitors, the identity of visitors, foraging behavior, flying pattern over inflorescence/flowers, landing pattern, visitation time, duration of visitation, floral reward obtained, contact with floral organs, and the behavior after leaving the flowers were recorded properly. Floral visitors were collected while foraging the flowers by using an insect capture net, then preserved in a solution of 70% ethyl alcohol for subsequent identification (Tandon *et al*., 2003; Athira et al., 2022).

Analysis of diversity of floral visitors

The diversity of floral visitors of *S. parameswaranii* was analyzed by Simpson's index, Shannon evenness and Shannon-Weiner index.

Shannon-Weiner index (H)

Shannon-Weiner index measures the floral visitor diversity in a community. It includes the relative abundance and species richness (Shannon and Weiner, 1963; Magurran, 2004; Raghavendra *et al*., 2018; Ranjitha *et al*., 2019).

$$H = -\sum p_i \times \ln p_i$$

Where, H is the Shannon-Weiner index, p_i is the proportion of individuals of a specific floral visitor compared to all floral visitors of *S. parameswaranii*.

Shannon evenness index (J')

Species evenness measures the degree of evenness in the floral visitor's community of both the study species. It is computed by dividing the observed diversity by the maximal diversity.

$$J' = \frac{H'}{H_{max}}$$

Where, J' is the evenness index, H' is the diversity observed and H_{max} is the maximum diversity observed (Shannon and Weiner, 1963; Magurran, 2004).

Simpson's index (D)

Simpson's index indicates the chances of two randomly chosen individuals of flower visitors in a community belonging to the same species.

$$D = 1-(\sum n_i (n_i - 1)/N (N - 1)$$

Here, n_i represents the total number of individuals of i^{th} species and N is the total number of individuals studied (Simpson, 1949; Magurran, 2004).

Visitation dominance of floral visitors

The Berger-Parker index was used to identify the dominant species among the floral visitors of *S. parameswaranii.*

Berger-Parker index (d)

It measures the dominance of a floral visitors in a community. It indicates the proportionate abundance of the most prevalent species (Berger and Parker, 1970; Magurran, 2004; Gunnarsson & Federsel, 2014).

$$d = \frac{ni}{NT}$$

Here, n_i denotes the number of individuals of the i^{th} species and NT represents the total number of individuals studied.

Pollination efficiency of floral visitors

Visitation frequency

To determine the visitation frequency, the total number of visits per flower within a specific period was measured. The visitation frequency of each floral visitor was determined by the following formula (Shivanna and Tandon, 2014).

$$\text{Visitation frequency} = \frac{\text{The total number of visits per flower per unit time}}{\text{Total number of flowers tagged for observation}}$$

Handling time (Ht)

The duration of a visit or total time spent by a visitor in a flower (Zych *et al*., 2013; Baranzelli *et al*., 2020), was calculated as follows,

$$\text{Handling time} = \text{Time of departure} - \text{Time of arrival}$$

Relative abundance (Ra)

The proportion of each floral visitor to the total number of floral visitors recorded (Baranzelli *et al*., 2020; Layek *et al*., 2022), was calculated by the following formula,

$$\text{Ra (\%)} = \frac{ni}{Ni} \times 100$$

Where, n*i* = Number of individuals of a particular visitor group of a species *i* in a plant species

N*i* = Total number of visitors recorded on a plant species

Activity Rate (AR)

The mean number of flowers visited per minute by a floral visitor is recorded as the activity rate (Talavera *et al*., 2001; Albano *et al*., 2009; Ajerrar *et al*., 2020).

Visitation rate index

The visitation rate index of each visitor category was determined by multiplying the frequency percentage by the activity rate (Talavera *et al*., 2001).

$I_{VR} = F \times AR$

Where, F represents the ratio of the number of individuals in an insect group to the total number of visitors recorded

AR= Activity Rate

Visitor activity index

The floral visitors and pollinators were differentiated by using the visitor activity index introduced by Ramírez, (2004) based on the five following qualitative parameters.

A. The occurrence or lack of pollen grains from the plant visited (1: copious, 0.5: less, and 0: no pollen).
B. The body part through which the pollen grains were carried and its alignment with the orientation and position of the androecium and gynoecium of the flowers (1: fulfilled, 0: not fulfilled).
C. The extent of pollen contact between the stigma of the flower and the body of the visitor (1: contact, and 0: no contact).
D. The association between the dimensions of the flower and the body size of the floral visitor (1: fulfilled, 0: not fulfilled).
E. Relative visits of the floral visitor (the number of visits per unit time).

The visiting species were considered pollinators when the first three parameters were fulfilled. The visitor activity index was computed using the following formula:

$$VA = \frac{(A \times B \times C) + (A \times B \times D \times E)}{2}$$

Here, the transfer of pollen grains is indicated by (A×B×C), while the adaptation, consistency and the attractiveness of the flower to the visitors are indicated by (A×B×D×E). The value of the visitor activity index was varied between zero to one. When there is a substantial deviation of VA values from zero, the floral visitor is designated as pollinator.

Statistical Analysis

The data of visitation frequency, relative abundance, visitation rate index and Berger-Parker index were analyzed by the Shapiro-Wilk test to find out the normality of distribution.

Due to the non-normal distribution, all these data were examined by the Kruskal-Wallis test and Dunn's post hoc test for pairwise comparisons by using the statistical software R version 4.1.0. All graphs were plotted with ggplot2 version 3.4.0 in R version 4.1.1 (R Core Team, 2021).

Results

Vegetative and flowering phenology

The initiation of leaf primordia of *S. parameswaranii* in 2019 was observed in the first week of January and few individuals experienced leaf flushing during early December. A partial leaf shedding was found during November in most of the marked individuals. The beginning of floral bud formation was recorded from the third week of December and observed as matured during early January. Floral buds began to open during the final week of January and the highest percentage of flowering (68%) was recorded in the third week of March. The flowering period ended in July and in some individuals, it has been extended to August. Fruit initiation and development were commenced at the end of June. The maturation of fruits was noticed towards the end of August with maximum intensity (14%) in October. All the tree individuals started dispersing the fruits from February onwards (Fig. 1).

In 2020, leaf flushing was recorded in November before flowering whereas, the abscission of the leaf was observed in August. The development of floral buds was noticed in the first week of December and the fully developed buds started opening in the first week of January. The flowering occurred from January to July with peak flowering intensity (75%) in March. In some of the trees, flowering was extended until August. Subsequently, the fruiting period was recorded from mid-June to December with a fruiting peak in October (15%). Fruiting was prolonged to January in some of the individuals and from November onwards, the fruits started to detach (Fig. 1).

In 2021, most of the marked individuals showed leaf emergence in November. Some of the individuals were exhibited leaf shedding in July whereas, in some others, leaf fall recorded in September. Similar to the previous years, flower bud initiation in 2021 was also noticed in December. The anthesis of flowers was recorded from the first week of January with a higher flowering intensity (70%) in March. Unlike the preceding years, the flowering was extended up to September and in a few individuals, it was continued until October. The initiation of fruits was observed from the end of June with maximum fruiting (13%) in October. Fruiting was completed in January and a few individuals observed up to February and the fruits started dispersing from the end of November (Fig. 1).

Vegetative and flowering phenology in relation to climatic variables

Pearson correlation indicated a significant positive correlation between temperature and flowering of *S. parameswaranii* for two years (2020: $r_{(10)} = 0.917$, $p<0.001$; 2021: $r_{(10)} = 0.774$, $p<0.005$) whereas it was positive, but not significant between temperature and flowering in 2019 ($r_{(10)} = 0.450$, $p = 0.1414$). A significant negative correlation was recorded between temperature and fruiting (2019: $r_{(10)} = -0.6189$, $p<0.05$; 2020: $r_{(10)} = -0.874$, $p<0.001$; 2021: $r_{(10)} = -0.797$, $p<0.005$) and no significant correlation was observed between rainfall and flowering & fruiting for the study periods (2019: flowering $r_{(10)} = 0.056$, $p = 0.8604$, fruiting $r_{(10)} = 0.025$, $p = 0.9381$; 2020: flowering $r_{(10)} = -0.454$, $p = 0.1375$, fruiting $r_{(10)} = 0.488$, $p = 0.1071$; 2021: flowering $r_{(10)} = -0.4815$, $p = 0.113$, fruiting $r_{(10)} = 0.483$, $p = 0.1111$). From the correlation analysis, it was confirmed that the reproductive phenoevents of both flowering and fruiting of *S. parameswaranii* were dependent on temperature (Fig. 2).

Morphology of floral parts and rewards

In *S. parameswaranii*, 154-875 inflorescences were produced per tree per peak flowering period and each inflorescence was reported to contain 23-55 flowers. The flowers were bisexual, actinomorphic, sub-sessile, pale yellowish-greenish and borne in panicles. The size of the flower was observed at 0.7-0.9 cm before anthesis and the slightly increased size to 0.9-2.5 cm after anthesis. Calyx tube was observed as long, funnel-shaped, greenish-yellow with 0.6-1.8 cm. Petals were four, free, imbricate, deciduous, calyptrate, and pale yellowish-green with 0.25-0.4 cm size. The stamen count per flower was recorded as 67-113 which is arranged on the rim of the calyx tube. The stamens are composed of long white filaments with 0.3-1 cm length. The ovary was observed as inferior, bicarpellary, bilocular and syncarpous with 24-26 ovules arranged in axile placentation. The length of style was recorded in the range from 0.3-0.7 cm which arises from the center of the hypanthial cup and the stigma was simple and wet.

In *S. parameswaranii*, each anther produced 1131.12±27.74 pollen grains and an average of 101800.8±2497.4 pollen grains per flower. The pollen grains were triangular, tricolporate with 13.26±0.77 µm. The pollen-ovule ratio of the species was determined to be 3915:1. Stigma receptivity began on the day of anthesis with 28%. A higher percentage (68%) of stigma receptivity was observed on the second day of anthesis. The receptivity was reduced on the following days but it was maintained up to six days (32%) after anthesis and no receptivity was observed thereafter. The volume of nectar was measured as 9.16±1.97 µl per flower and its sugar concentration was measured as 3-12% Brix. Apart from nectar, a sufficient quantity of pollen grains (101800.8±2497.4/flower) was served as a reward for floral visitors.

In the case of *S. parameswaranii*, the floral advertisement was provided by dense stamens. In the absence of attractive petals or sepals, the strong fragrance also acted as the major olfactory attractant to attract floral visitors. The ovule/seed ratio was calculated as 25:1 in *S. parameswaranii*. The fruits were observed as scarlet red, single-seeded, elongated berries with 1.3±0.18 cm length and 0.65±0.21 cm diameter with persistent calyx at the top of the crown (Fig. 3).

Floral visitors and their foraging behaviour

The flowers *S. parameswaranii* provided both pollen grains and nectar to the floral visitors. A total of 12 insect species including Hymenoptera (*Scolia dubia*, *Camponotus* sp., bee 1, bee 2 and wasp), Lepidoptera (moth and butterfly), Coleoptera (Scarab beetle and beetle) and Diptera (*Chrysomya* sp., *Plecia nearctica* and *Sphaerophoria scripta*) were documented as the floral visitors of *S. parameswaranii*. Among them, most of the floral visitors viz., *Scolia dubia*, *Chrysomya* sp., *Sphaerophoria scripta*, bee 1, bee 2, beetle and wasp were foraged both pollen and nectar. *Camponotus* sp., *Plecia nearctica*, butterflies and moths were exclusively visited for nectar whereas, the Scarab beetles consumed the stamens without executing any pollination duties (Table 1 & Fig. 4).

Diversity and dominance of floral visitors

The Shannon-Weiner diversity index of floral visitors in *S. parameswaranii* stayed similar (2.3-2.31) during 09.00-13.00 h. Species diversity was recorded as a minimum (0.72) during 06.00-07.00 h. Species evenness was also more or less similar (0.94-0.96) from 08.00-14.00 h whereas evenness was recorded as least (0.66) during 06.00-07.00 h (Fig. 5). Simpson's index of floral visitor diversity was calculated as maximum (0.9) from 09.00-13.00 h and minimum (0.42) during 06.00-07.00 h.

Camponotus sp. was observed as the most dominant (0.21) floral visitor of *S. parameswaranii*. *Scolia dubia* and Scarab beetle were equally dominant and forage effectively among the floral visitors of *S. parameswaranii* with a higher dominance index (0.13). Bee 1 was observed with a dominance index value of 0.12 and *Chrysomya* sp. and Bee 2 shared equal dominance value (0.11). Similarly, *Sphaerophoria scripta*, wasp and moth were recorded with similar dominance (0.07) values. Berger-Parker index of beetles was recorded as 0.08 and the least dominance (0.05) was experienced by *Plecia nearctica* and butterfly (Fig. 6). The differences between the Berger-Parker index of floral visitors in the visitor community of *S. parameswaranii* were calculated as very significant (χ^2 = 33.91, df = 11, p <0.001). The pairwise comparisons using Dunn's test with Bonferroni correction verified the significant

differences between the Berger-Parker index of *Scolia dubia* and butterfly ($p < 0.05$) and between *Scolia dubia* and *Plecia nearctica* ($p < 0.01$).

Pollination efficiency of floral visitors

During floral visitation, *S. dubia* has responded with maximum visitation frequency per unit time (0.78±0.11) followed by bee 1 (0.75±0.09), bee 2 (0.68±0.11), *Chrysomya* sp. (0.60±0.10), Scarab beetle (0.59±0.09), wasp (0.50±0.10), *Sphaerophoria scripta* (0.46±0.12), butterfly (0.44±0.06), *Camponotus* sp. (0.35±0.03), *Plecia nearctica* (0.32±0.08), beetle (0.21±0.02) and moth (0.12±0.03) (Table 1 & Fig. 7). Kruskal-Wallis test indicated the significant differences in the visitation frequency of each floral visitor ($\chi^2 = 34.15$, df = 11, $p < 0.001$). Pairwise comparisons by Dunn's test with Bonferroni correction confirmed the significant differences in visitation frequency of *Scolia dubia* and beetle ($p < 0.005$) and between beetle and bee 1 ($p < 0.01$). *Camponotus* sp. (95.9±5.14 sec.) and Scarab beetles (91.6±4.45 sec.) spent significantly more time per visit in the flowers and it was lowest (4.9±0.52 sec.) by moths in the flowers of *S. parameswaranii*. The beetles have also spent higher time (57.4±2.90 sec.) in flowers followed by *Scolia dubia* (17.5±2.10 sec.), bee 2 (12.1±0.70 sec.), *Sphaerophoria scripta* (11.3±0.86 sec.), wasp (10.4±0.66 sec.), *Chrysomya* sp. (10.1±0.64 sec.), bee 1 (9.5±0.95 sec.), *Plecia nearctica* (8±0.88 sec.) and butterfly (5.4±0.73 sec.) (Table 1).

Camponotus sp. was recorded as the most abundant (21.5±7.34%) floral visitor of *S. parameswaranii* followed by *Scolia dubia* (13.77±0.99%), Scarab beetle (13.36±1.66%), bee 1 (12.66±0.79%), *Chrysomya* sp. (11.36±1.10%), bee 2 (11±0.89%), beetle (8.8±1.88%), *Sphaerophoria scripta* (7.87±1.24%), wasp (7.44±1.15%), moth (7.33±3.84%), butterfly (5.57±1.41%) and *Plecia nearctica* (5±1.38%) (Table 1). Significant differences were observed in the relative abundance among the floral visitors of *S. parameswaranii* ($\chi^2 = 34.14$, df = 11, $p < 0.001$). Multiple comparison methods showed that the significant variations observed in the abundance were due to the activity of *Scolia dubia* and *Plecia nearctica* ($p < 0.005$), *Plecia nearctica* and bee 1 ($p < 0.05$) and *Scolia dubia* and butterfly ($p < 0.05$).

In *S. parameswaranii*, bee 1 visited more flowers per minute (3±0.47) followed by Scarab beetle (2.9±0.37), butterfly (2.7±0.36), *Scolia dubia* (2.7±0.26), *Plecia nearctica* (2.7±0.21), bee 2 (2.6±0.4), *Chrysomya* sp. (2.5±0.58), *Camponotus* sp. (2.2±0.32), wasp (2.1±0.23), *Sphaerophoria scripta* (2±0.21), moth (1.6±0.22) and beetle (1.6±0.22) (Table 1).

Visitation rate index

From the observation, it was found that *Camponotus* sp. was recorded with maximum visitation rates (0.46) and moths were recorded with the least visitation rates (0.11). Scarab

beetles and bee 1 were recorded with an equal range of visitation rates (0.38) and the visitation rate index of *Scolia dubia* was recorded as 0.36. The visitation rate of *Chrysomya* sp. and bee 2 was recorded as 0.28. *Sphaerophoria scripta* and wasps were also observed with similar visitation rates (0.15). The I_{VR} of butterfly, beetle, *Plecia nearctica* and moths were calculated as 0.14, 0.13, 0.13 and 0.11 respectively (Table 1 & Fig. 8). Kruskal-Wallis test detected significant differences in the visitation rate indices of floral visitors of *S. parameswaranii* (χ^2 =51.95, df = 11, $p<0.001$). Further, the multiple comparison methods have indicated significant differences in the I_{VR} due to the activity of beetle vs. bee 1 ($p <0.005$), *Plecia nearctica* vs. bee 1 ($p <0.005$), *Scolia dubia* vs. beetle ($p <0.01$) and *Scolia dubia* vs. *Plecia nearctica* ($p <0.01$).

Visitor activity index

Scolia dubia was recorded as the legitimate pollinator of *S. parameswaranii* due to the abundance of pollen grains held in their body, effective stigma contact, association with floral size and frequent visits. Also, they were recorded with a higher visitor activity index (0.89). The flowers of *S. parameswaranii* produced a large quantity of stamens and pollens. The pollens were found in the bodies of most of the visitors, such as *Scolia dubia*, *Camponotus* sp., *Chrysomya* sp., *Sphaerophoria scripta*, bee 1, bee 2, wasp and Scarab beetle during floral visit. Besides beetles, butterflies and moths, and all other visitors were made effective contact with the stigma. However, *P. nearctica* and Scarab beetle made occasional stigma contact and the visitor activity index was recorded as a minimum. Due to its visitation behaviour, it has been considered as floral visitors. Of the twelve floral visitors recorded, seven of them were recorded as pollinators whereas the remaining were designated as floral visitors. Maximum visitor activity index was recorded for *Scolia dubia* (0.89) followed by bee 1 (0.87), bee 2 (0.84), *Chrysomya* sp. (0.8), wasp (0.75), *Sphaerophoria scripta* (0.73) and *Camponotus* sp. (0.67) and was regarded as pollinators. The remaining five such as *Plecia nearctica* (0.08), Scarab beetle (0.29), beetle (0), butterfly (0), and moth (0) with minimum activity index were observed as floral visitors (Table 1 & Fig. 8 & Fig.9).

Discussion

Phenology

There was no accurate seasonal pattern was observed in the vegetative phenophases of *S. parameswaranii*. Leaf flushing and leaf shedding were recorded simultaneously without any distinct peaks. Similarly, *S. occidentale* and *S. caryophyllatum* were exhibited leaf flushing and leaf fall throughout the year (Varghese and Sreekala, 2017; Nadarajan and Pujari, 2019). Whereas, the reproductive phenoevents of tropical tree species were significantly controlled by

the availability of rainfall (McLaren and McDonald, 2005; Singh and Krishna, 2006; Mohandass *et al*., 2018).

The flowering season of *S. parameswaranii* was recorded from January to July and a fruiting season from June to December. Similarly, the other species of *Syzygium* such as *S. syzygioides* (Lack and Kevan, 1984), *S. sayeri* (Boulter *et al*., 2005), *S. cuminii* (Bajpai *et al*., 2012), *S. alternifolium* (Raju *et al*., 2014), *S. occidentale* (Varghese and Sreekala, 2017), *S. caryophyllatum* (Nadarajan and Pujari, 2019; Geethika and Sabu, 2017) were also reported with blooming and fruiting at single phase. The flowering and fruiting of *S. parameswaranii* were significantly related to temperature but not related to rainfall. In the same manner, the flowering of *S. caryophyllatum* has significantly correlated with temperature and was not correlated with rainfall (Nadarajan and Pujari, 2019). The role of temperature in the vegetative and reproductive phenoevents of flowering plants has been addressed by many researchers. Regulatory modules use temperature signals to regulate gene expression and help plants in physiological changes from germination to blooming. These regulatory modules manage both morphological and molecular reactions of plants in response to changes in temperature (Capovilla et al., 2015; Brightbill and Sung, 2022). The vegetative growth and flowering pattern of many plant species is dependent on ambient temperature which stimulates the initiation and development of meristem (Lobell and Field, 2007; Long and Ort, 2010; Brightbill and Sung, 2022).

There were limited researches conducted to understand the relationship between climatic factors and reproductive phenoevents in the genus *Syzygium* (Nadarajan and Pujari, 2019). However, the influence of temperature in flowering was reported in other sister genera of the family Myrtaceae such as *Acca* (Ramirez and Kallarackal, 2018), *Eucalyptus* (Hudson *et al*., 2015; Hudson and Keatley, 2013; Keatley *et al*., 2002; Arnold and Dongyun, 2003; Keatley and Hudson, 2000; Hudson *et al*., 2009; Hudson *et al*., 2010), *Melaleuca* (Baskorowati *et al*., 2010); *Psidium* (Normand and Habib, 2001); *Leptospermum* (Bicknell and Jaksons, 2018; O'Brien and Calder 1993; Zieslin and Gottesman, 1986); *Xanthostemon* (Nasayao, 1994), *Hypocalymma* (Day, 1992), *Plinia* (Oliveira *et al*., 2019), *Campomanesia* (Rodrigues *et al*., 2017), *Kunzea* (Gallagher *et al*., 2009).

Does the floral morphology attract floral visitors?

Floral morphology and its functional characteristics have a significant role in the reproductive success of a plant (Navarro and Guitian, 2002). In *S. parameswaranii*, the flowers were arranged in panicles, as in *S. megacarpum* (Chantaranothai and Parnell, 1994) and *S. pycnanthum* (Mudiana and Ariyanti, 2010). *Syzygium parameswaranii* has the least quantity

(23-55 nos.) of flowers per inflorescence when compared to other species of *Syzygium* (Raju *et al*., 2014; Geethika and Sabu, 2017; Athira *et al*., 2022) and the stamens were arranged on the rim of the hypanthial cup at various lengths. This type of stamen arrangement was also reported in most species of *Syzygium* and also in *S. alternifolium* (Raju *et al*., 2014), *S. travancoricum* and *S. heyneanum* (Kuriakose *et al*., 2018a) which attract floral visitors considerably. As like in other species, *S. parameswaranii* has joined petals to form a cap-like structure over the bud called calyptra. This calyptra fell off during anthesis due to internal pressure from the stamens. During the bud stage, the stamens were bent inwardly and further straightened at the time of anthesis, projected out from the flowers and showing their shape towards floral visitors. Similar advertisement and reward patterns were reported to effect pollination in other species of *Syzygium* (Varghese and Sreekala, 2017; Geethika and Sabu, 2017; Kuriakose *et al*., 2018a). Vasconcelos *et al*. (2015), studied the stamen position in the family Myrtaceae and reported three types of stamens; straight stamens, semi-curved stamens and completely incurved stamens.

Syzygium parameswaranii was observed with incurved stamens during the pre-anthetic stage and the anthers were dehisced after anthesis. Kuriakose *et al*. (2018b) reported the dehiscence of anthers in *S. occidentale* two days before anthesis. Whereas it was documented one day before anthesis in *S. occidentale* (Varghese and Sreekala, 2017). *Syzygium parameswaranii* was observed with a wet stigma without papillae. The presence of wet stigma was reported in the case of *S. occidentale* (Varghese and Sreekala, 2017; Geethika and Sabu, 2017) and *S. alternifolium* (Raju *et al*., 2014). The stigmatic receptivity of *S. parameswaranii* was started on the day of anthesis and became optimum on the second day of anthesis and decreased gradually and completely lost its receptivity on the seventh day. *Syzygium parameswaranii* exhibited a prolonged period of stigma receptivity when compared to the other species of *Syzygium* such as *S. sayeri* (Boulter *et al*., 2005), *S. alternifolium* (Raju *et al*., 2014), *S. occidentale* (Varghese and Sreekala, 2017), *S. aqueum* and *S. jambos* (Nacata *et al*., 2019). This behaviour is due to the poor advertisement and reward of the flowers towards attraction of visitors. By retaining the receptivity of flowers as longer period, there will be a possibility of getting viable pollen grains from the foreign flowers

Despite the limited floral advertisements and rewards in *S. parameswaranii*, the presence of numerous anthers promote and ensures successful reproduction. Each anther recorded with adequate pollen grains (1131.12±27.74 pollen grains/anther and 101800.8±2497.4 pollen grains/flower) like other species of *Syzygium*, *S. occidentale* (Varghese and Sreekala, 2017; Kuriakose *et al*., 2018b), *S. alternifolium* (Raju *et al*., 2014), *S.*

jambos and *S. megacarpum* (Chantaranothai and Parnell, 1994), *S. travancoricum*, *S. mundagam, S. heyneanum* and *S. laetum* (Kuriakose *et al*., 2018a). Most species of Myrtaceae have triangular and tricolporate pollen grains, especially in the genus *Syzygium* (Parnell, 2003). The other species such as *S. malaccense*, *S. aqueum, S. jambos* (Nacata *et al*., 2019), *S. caryophyllatum* (Geethika and Sabu, 2017), *S. occidentale* (Varghese and Sreekala, 2017), *S. alternifolium* (Raju *et al*., 2014), *S. cuminii* (Bajpai *et al*., 2012), *S. sayeri* (Boulter *et al*., 2005), *S. jambos* (Chantaranothai and Parnell, 1994) were also recorded with triangular, tricolporate pollen grains with a size ranging from 7-18 µm. The pollen grains of *S. parameswaranii* were recorded as 13.26±0.77 µm. In *S. parameswaranii*, a total of 26 ovules were recorded and only one developed as a seed. Similar findings have been documented in other Myrtaceae species (Badou *et al*., 2020; Geethika and Sabu, 2017; Raju *et al*., 2014; Varghese and Sreekala, 2017; Lughadha and Proença, 1996; Arathi *et al*., 1996). As stated by the previous author (Krishnamurthy *et al*., 1997), the higher ovule abortion rate was recorded due to a diffusible indole compound secreted by the dominant ovule to prevent the development of other ovules from resource uptaking. Of the 26 ovules developed in the ovary, the dominant ovule has suppressed the growth and development of the remaining ovules in the case of *S. parameswaranii*. However, further detailed researches are required to understand the mechanism behind it. This was supported by Raju *et al*. (2014), who also suggested that the ovule abortion in *S. alternifolium* may be due to the above reason. In *S. parameswaranii*, the pollen-ovule ratio was calculated as higher (3915:1), similar to that of 1349:1 in *S. occidentale* (Varghese and Sreekala, 2017), 1819:1 in *S. myhendrae* (Athira *et al*., 2022), 1872:1 in *S. caryophyllatum* (Geethika and Sabu, 2017), and 5800:1 in *S. jambos* (Chantaranothai and Parnell, 1994). The higher pollen-ovule ratio indicates that the species rely on external agents for pollination through outcrossing (Varghese and Sreekala, 2017; Athira *et al*., 2022). The pollen production and pollen-ovule ratio of *S. parameswaranii* have confirmed that this species needs external agents to transfer pollen to the stigma.

Do floral traits and rewards effect floral visitation by agents?

To attract and handle the sexual parts of the flowers by the floral visitors, flowers offer multifaceted cues and rewards (Latty and Trueblood, 2020). According to many authors, floral morphology has a critical role in attracting floral visitors and pollinators and changes in floral morphology influence the behaviour of pollinators (Spaethe *et al*., 2001; Whitney and Glover, 2007; Krishna and Keasar, 2018). The floral traits of *S. parameswaranii* are ineffective in attracting seven species of floral visitors due to its lack of vibrant or appealing sepals or petals. According to evolutionary biologists, floral colour diversity is a tactic in plants to advertise

their presence to attract pollinators and effect successful pollination (Gumbert *et al*., 1999; Raguso, 2004). In general, floral pigmentation helps to maximize the pollinators attraction and attractive coloured petals serve as the major visual cue for floral visitors (Miller *et al*., 2011). Unfortunately in *S. parameswaranii*, the flowers were not much focused on attracting floral visitors by their color, size, shape, structure, extra floral appendages and ornamentation. The flower holds the greenish sepals formed as cup-like hypanthium with pale yellow-greenish calyptrate petals. The strong floral scent of *S. parameswaranii* has acted as an olfactory attractant to attract a diversity of pollinators when the flowers open. Similarly, flowers of *S. occidentale* were reported with an aromatic odour (Varghese and Sreekala, 2017) to attract floral visitors. In plant-pollinator interactions, flowers act as a marketplace, where nectar and pollen grains are the products or floral rewards and floral colour, shape and odour are served as advertisements (Ollerton, 2006; Gumbert *et al*., 1999). According to Lughadha and Proença (1996), stamens are the most noticeable structures of the flowers in the family Myrtaceae. In the case of *S. parameswaranii*, the large number of stamens (67-113/flower) served as a major floral advertisement in the absence of colourful or attractive petals or sepals. Few studies only emphasized floral biology which has explained the importance of floral rewards (pollen and nectar) provided by the members of *Syzygium* (Varghese and Sreekala, 2017; Pillai and Sreekala, 2021; Athira *et al*., 2022), but none of the studies pointed out the role of dense stamens as a visual attractant. In *S. parameswaranii*, the large number of stamens (67-113) attracted a wide range of floral visitors which effected pollination. The quantity of nectar in *S. parameswaranii* was recorded as less (9.16±1.97 µl) and its utilization as a reward may not effectively attract pollinators towards flowers. Similarly, it was reported with poor nectar quantity (12.7 µl) in *S. alternifolium* (Raju *et al*., 2014), *S. heyneanum* (11.06±0.8 µl) and *S. laetum* (22.25±0.27 µl) (Kuriakose *et al*., 2018a).

Diversity and dominance of floral visitors

Only a limited studies have been attempted to analyze the abundance and diversity of floral visitors and few studies have been undertaken to investigate the diversity and dominance of floral visitors of tree species. However, a few investigators used different diversity indices including the Shannon-Weiner index, Shannon evenness index, Simpson's index and Berger-Parker index to study the diversity, abundance and dominance of floral visitors in trees (Dar *et al*., 2018; Raghavendra *et al*., 2018; Sheela and Rose, 2021). These indices can provide information on both the diversity of floral visitors and the relative abundance of a specific floral visitor species to the total floral visitor community associated with a particular plant species (Magurran, 2004; Raghavendra *et al*., 2018; Ranjitha *et al*., 2019).

In *S. prameswaranii*, the Shannon-Weiner diversity index has shown relatively similar values during the time period of 09.00-13.00 h, and it has suggested the consistency and stability of floral visitor diversity during the time. A minimum value of the Shannon-Weiner index was recorded during 06.00-07.00 h which showed the low diversity and the visitor community was dominated by only a few species (*Camponotus* sp. and beetles). A more or less similar evenness index observed during 08.00-14.00 h has suggested the balanced nature of the relative abundance of various floral visitors of the visitor community. Berger-Parker index was used to find out the dominant species in the floral visitor community of *S. parameswaranii*. In the case of *S. parameswaranii*, *Camponotus* sp. was found as dominant among the various floral visitors recorded. They visited the flowers to collect nectar and the bunch of stamens permitted the free movements of *Camponotus* sp. and acted as shelter for them.

Due to poor advertisements and rewards, the number of floral visitors attracted towards the flowers of *Syzygium* was limited and few of them attracted a large number of pollinators. The flowers of *S. tierneyanum* attracted 45 floral visitors (Hopper, 1980), *S. alternifolium* attracted 33 floral visitors (Raju *et al*., 2014) and *S. heyneanum* was reported to 23 floral visitors (Kuriakose et al., 2018a). The inflorescence of *S. laetum* was visited by four groups of floral visitors, *S. mundagam* was reported with eight visitors (Kuriakose *et al*., 2014a), and *S. myhendrae* was reported with eight visitors (Pillai and Sreekala, 2021) and 10 floral visitors (Athira *et al*., 2022). Similarly, *S. parameswaranii* was also visited by twelve floral visitors. This may be due to the lack of advertisement or rewards provided by the flowers of *S. parameswaranii*. These flowers were observed to be devoid of colourful petals or sepals and they offer only a low quantity of nectar (9.16±1.97 µl). The presence and abundance of floral visitors in plant-pollinator interactions are also significantly influenced by climate change (Forrest, 2014; Rafferty, 2017; Olsen *et al*., 2022) and habitat fragmentation (Rathcke and Jules, 1993; Abramson *et al*., 2011; Xiao *et al*., 2016).

Syzygium parameswaranii exhibited the least diversity of floral visitors and a relatively lower number of pollinators in comparison to other species of *Syzygium*. So, a large number of pollinators may facilitate to improvement of the fruit formation in *S. parameswaranii*. The species distribution was documented across different forest areas of Megamalai Wildlife Sanctuary such as Collector Kadu, Thennasimettai, Varayadu Motta, Kardana Estate, Pachakumatchi hills and Highwavies Estate. Nevertheless, Cardamom, coffee and tea plantations replaced a large area of its habitat of montane rainforests of Megamalai Wildlife Sanctuary which created a barrier between the population (Ganesh *et al*., 2014; Athira and Ramasubbu, 2020). The migration of insects between the population of *S. parameswaranii*

through the commercial plantations were affected severely by the uncontrolled pesticide application (Athira and Ramasubbu, 2020). Similarly, floral visitors may be threatened by the intense usage of pesticides by the planters. Implementing a controlled spray of pesticides in plantation areas will effectively safeguard a significant number of floral visitors of *S. parameswaranii* and other threatened species.

Pollinators and their foraging behaviour

Insects are the only potential foragers of flowers of *Syzygium* and species like honey bees, *Apis dorsata*, *A. cerana*, *A. mellifera*, *A. mellifera adansonii*, *A. florea* (Chantaranothai and Parnell, 1994; Mudiana and Ariyanti, 2010; Djonwangwe *et al*., 2011; Raju *et al*., 2014; Varghese and Sreekala, 2017; Geethika and Sabu, 2017; Kuriakose *et al*., 2018a; Nadarajan and Pujari, 2019; Kuriakose *et al*., 2018b; Pillai and Sreekala, 2021), *Trigona* sp. (Raju *et al*., 2014; Varghese and Sreekala, 2017;Geethika and Sabu, 2017; Kuriakose *et al*., 2018a; Kuriakose *et al*., 2018b; Pillai and Sreekala, 2021), wasps (Hopper, 1980; Raju *et al*.,2014; Geethika and Sabu, 2017; Nadarajan and Pujari, 2019; Kuriakose *et al*., 2018a), butterflies (Hopper, 1980; Chantaranothai and Parnell, 1994; Mudiana and Ariyanti, 2010; Raju *et al*., 2014, Nadarajan and Pujari, 2019; Kuriakose *et al*., 2018a), flies (Hopper, 1980; Raju *et al*., 2014; Nadarajan and Pujari, 2019; Kuriakose *et al*., 2018a), hawkmoths (Raju *et al*., 2014), hoverflies and halictid bees (Kuriakose *et al*., 2018), carpenter bees and bugs (Nadarajan and Pujari, 2019) and ants (Hopper, 1980; Crome and Irvine, 1986; Chantaranothai and Parnell, 1994; Mudiana and Ariyanti, 2010; Nadarajan and Pujari, 2019; Kuriakose *et al*., 2018b) were recorded as foragers by various researchers.

The higher pollen production and fragrance in *S. parameswaranii* seems to function as only advertisement and a real reward to attract floral visitors towards the flowers. Russell *et al*. (2016) have reported that most bee species forage pollen as a real floral reward other than nectar. This has been confirmed by the presence of corbiculum or pollen baskets on the bodies of bees (Shivanna and Tandon, 2014). Previous studies (Osche, 1983; Lunau, 2000; Heuschen *et al*., 2005; Jorgensen *et al*., 2006; Lunau *et al*., 2017) have reported the advertising purpose of stamens in flowers, where pollen grains served as a visual signalling mechanism. *Syzygium parameswaranii* has numerous (67-113) stamens with elongated white filaments and yellow anthers that act as a visual attractant for floral visitors.

The flowers of *S. parameswaranii* were exclusively visited by insects belonging to four orders namely Hymenoptera, Diptera, Lepidoptera and Coleoptera like the flowers of *S. guiineense* subsp. *macrocarpum* (Badou *et al*., 2020). Many species of ants were reported as floral visitors of various species of *Syzygium* (Hopper, 1980; Crome and Irvine, 1986;

Chantaranothai and Parnell, 1994; Geethika and Sabu, 2017; Kuriakose *et al*., 2018b; Nadarajan and Pujari, 2019) including *S. parameswaranii*. *Technomyrmex albipes*, an ant species was reported as the most effective pollinator than other insect and bird visitors of *S. occidentale* (Kuriakose *et al*., 2018b). The nectar-robbing behaviour of *Camponotus parius* was reported in *S. caryophyllatum* (Geethika and Sabu, 2017) and *Callistemon citrinus* (Sharanya *et al*., 2014). *Camponotus* sp. visited the flowers for nectar and was recorded as the most abundant and dominant visitor of *S. parameswaranii* which was recorded with a higher visitation rate index and activity index. Similarly, the other species of *Camponotus* were also reported as floral visitors of members of Myrtaceae (Beardsell *et al*., 1993; Tope *et al*., 2012; Nucci and Alves-Junior, 2017). The position and arrangement of stamens around the hypanthial cup of *Syzygium* help the ants to crawl through the flowers and come in contact with the stigma (Kuriakose *et al*., 2018). Similarly, in *S. parameswaranii*, nectar served as the reward and a similar mechanism was observed.

In the case of flowers of *S. parameswaranii*, three species of fly were recorded as floral visitors (*Chrysomya* sp., *Plecia nearctica* and *Sphaerophoria scripta* or Syrphid flies). Likewise, the flowers of *S. travancoricum* were frequently visited by Syrphid fly and Muscoid flies (Kuriakose *et al*., 2018a) and the flowers of *S. laetum* were also visited by the hoverfly. The flowers of *S. myrtifolium* were recorded with *Chrysomya megacephala* as floral visitors (Mudiana and Ariyanti, 2021). An unidentified moth has visited the flowers of *S. parameswaranii* during the daytime. Similarly, the activity of diurnal moths was reported previously in some of the *Syzygium* members. Hopper (1980) documented four species of diurnal moths from the flowers of *S. tierneyanum*. Raju *et al*. (2014) have also recorded diurnal moths as floral visitors of *S. alternifolium*. In the case of *S. parameswaranii*, the moths were ineffective in facilitating pollination as they were unable to establish effective contact with the stigma.

The present study has differentiated legitimate pollinators from casual floral visitors by determining the visitor activity index. Of the 12 floral visitors of *S. parameswaranii*, seven of them such as *Scolia dubia* (0.89), bee 1 (0.87), bee 2 (0.84), *Chrysomya* sp. (0.8), wasp (0.75), *Sphaerophoria scripta* (0.73), *Camponotus* sp. (0.67) were recorded as pollinators and the remaining were recorded as casual floral visitors based on the visitor activity index. Among them, *Scolia dubia* was recorded as the effective pollinator of *S. parameswaranii* due to their higher visitation frequency, relative abundance and visitor activity index. Similarly, *Scolia* sp. was also reported as a pollinator of *S. caryophyllatum* (Nadarajan and Pujari, 2019).

The floral traits of *S. parameswaranii* suggested that they were adapted to attract insect visitors. Although, bird pollination was reported in few *Syzygium* species such as *S. tierneyanum* (Hopper, 1980; *S. cormiflorum* (Crome and Irvine, 1986); *S. mamillatum* (Kaiser *et al*., 2008) *S. laetum*, and *S. mundagam* (Kuriakose *et al*., 2018a), whereas, no birds were recorded as visitors of the flowers of *S. parameswaranii* throughout the observation time. Because bird-pollinated species exhibited a floral syndrome characterized by the presence of large flowers, red-coloured floral parts and an abundance of diluted nectar (Cronk and Ojeda, 2008; Kuriakose *et al*., 2018b). Such floral traits have not been observed in *S. parameswaranii*. Anemophily was reported in some of the *Syzygium* species such as *S. leuhmanni* (Sanewski, 2010), *S. cuminii* (Bajpai *et al*., 2012), *S. caryophyllatum* (Geethika and Sabu, 2017), *S. laetum* and *S. mundagam* (Kuriakose *et al*., 2018a). Although, the present study has not assessed the wind pollination mechanism, the physical disturbances caused by floral visitors during their foraging released pollen grains to the surrounding environment which may lead to the pollination by wind in *S. parameswaranii*.

Conclusion

In conclusion, this study comprehensively investigated the phenology, floral biology and pollination ecology of endemic and endangered *S. parameswaranii*. The floral morphology of *S. parameswaranii* has no significant role in plant-pollinator interactions, whereas an abundance of stamens and strong fragrance only act as the floral attractant to some extent in the absence of colourful perianth in *S. parameswaranii*. Here, the stamens serve a dual purpose, functioning as both an advertisement and a reward for floral visitors. *Syzygium parameswaranii* compensated for its limited floral advertisement and nectar production by offering abundant pollen grains as the primary floral rewards. However, advertisements and rewards for the flower have not supported the successful reproduction of this endangered tree. Moreover, this may also be a reason why this tree has been restricted to a few localities of the Western Ghats of India. And also be a reason behind the rarity of this tree species. Hence, most of the individuals are growing within commercial plantations, and implementing a controlled usage of pesticides becomes crucial to safeguard a considerable number of floral visitors. Employing this approach helps to maintain the diversity and abundance of pollinators within the plantation areas.

Conflict of interest

The authors declare no conflicts of interest.

Contributing author details

Athira Reghunath; Execution of field and laboratory studies, Preparation of Manuscript; Anjana Surendran; Assisted in execution of field and laboratory studies Raju Ramasubbu: Planning of research problem, Lead, Review and Editing of Manuscript.

Acknowledgements

The authors are extremely thankful to the Department of Science and Technology, Government of India for providing funds under the INSPIRE Fellowship (IF180084) to execute this research work. We also thank PCCF& CWW, Ref. No. WL (A)/45498/ 2018, dt. 05/12/2018 (Permit No. 77/2018), Tamil Nadu Forest Department for the permission to carry out the work.

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Figures



Figure 1

A) Leaf flushing in mature individuals; B) Adult individual of *S. parameswaranii* at peak flowering; C) A flowering branch with anthesis of flowers; D) Branch with fruit formation; E) Mature fruits

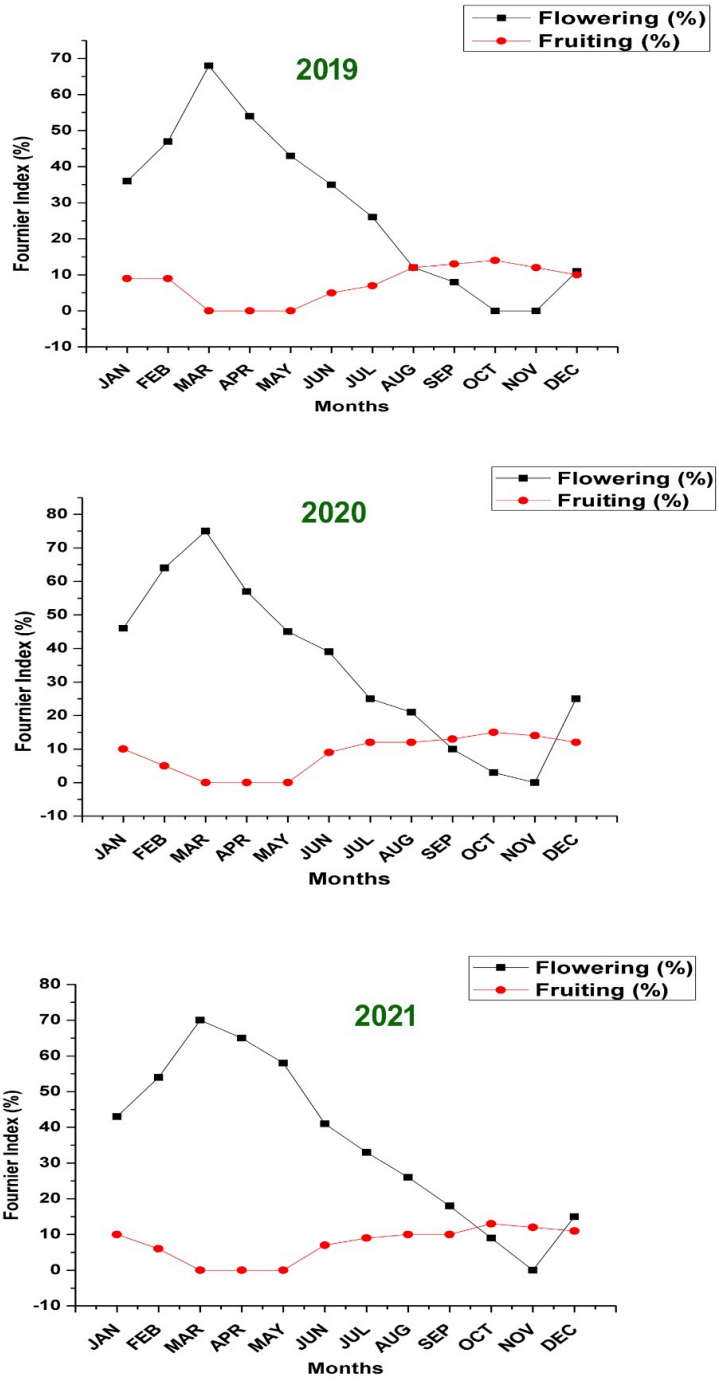


Figure 2

Flowering and fruiting intensity of *S. parameswaranii*

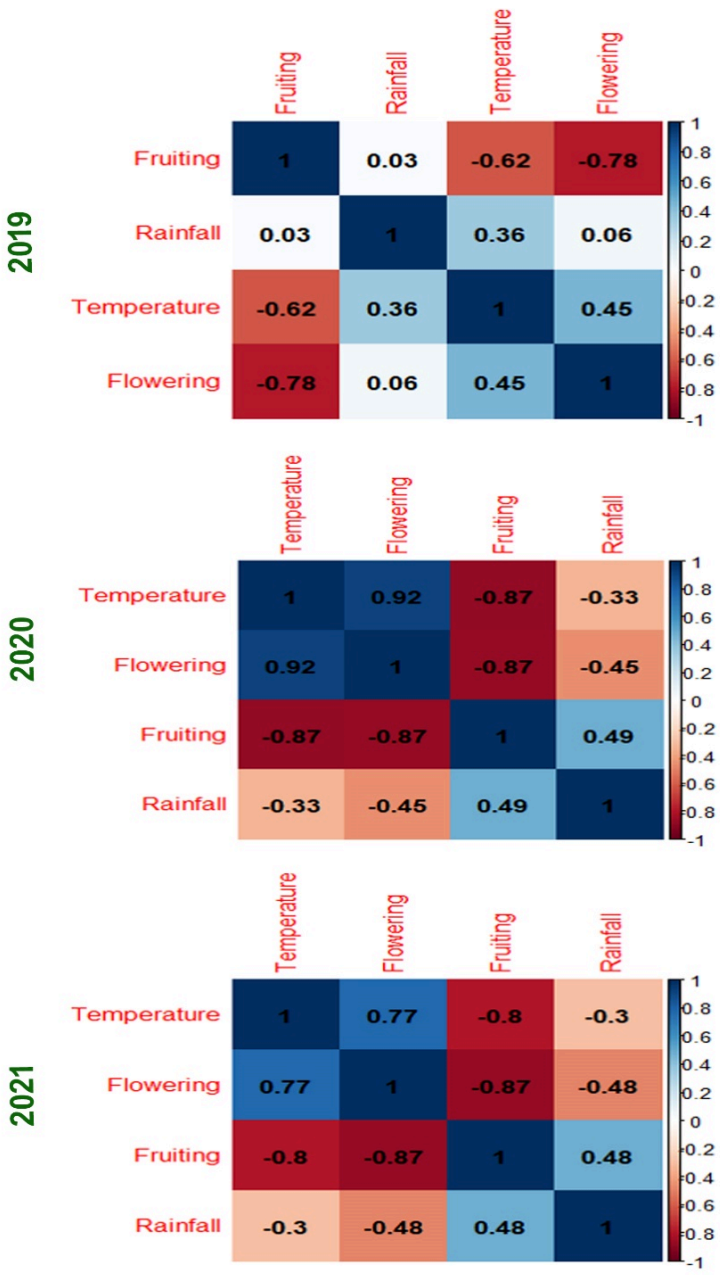


Figure 3

Impact of climatic variables on flowering and fruiting of *S. parameswaranii*



Figure 4

Floral morphology of *S. parameswaranii*: A) Flower bud; B) Mature flower; C) L.S. of mature flower; D) L.S. of hypanthium; E) Petal; F) Stamens; G) Anther; H) Ovule



Figure 5

Floral visitors of *S. parameswaranii*: A) *Scolia dubia*; B) *Plecia nearctica*; C) *Chrysomya*sp.; D) Beetle; E) Scarab beetle; F) *Sphaerophoria scripta*; G&H) *Camponotus* sp.

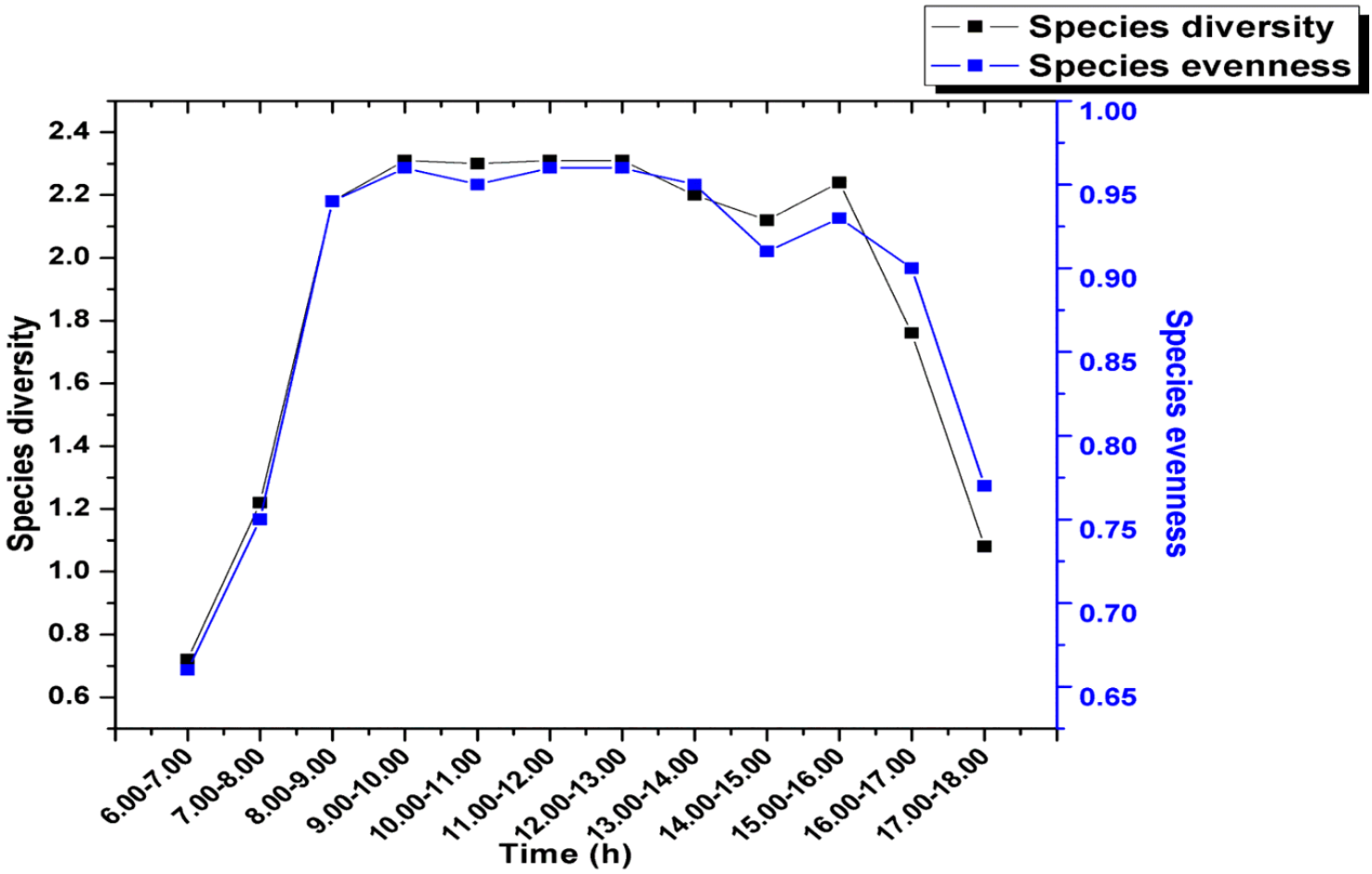


Figure 6

Diversity of floral visitors on the flowers of *S. parameswaranii*

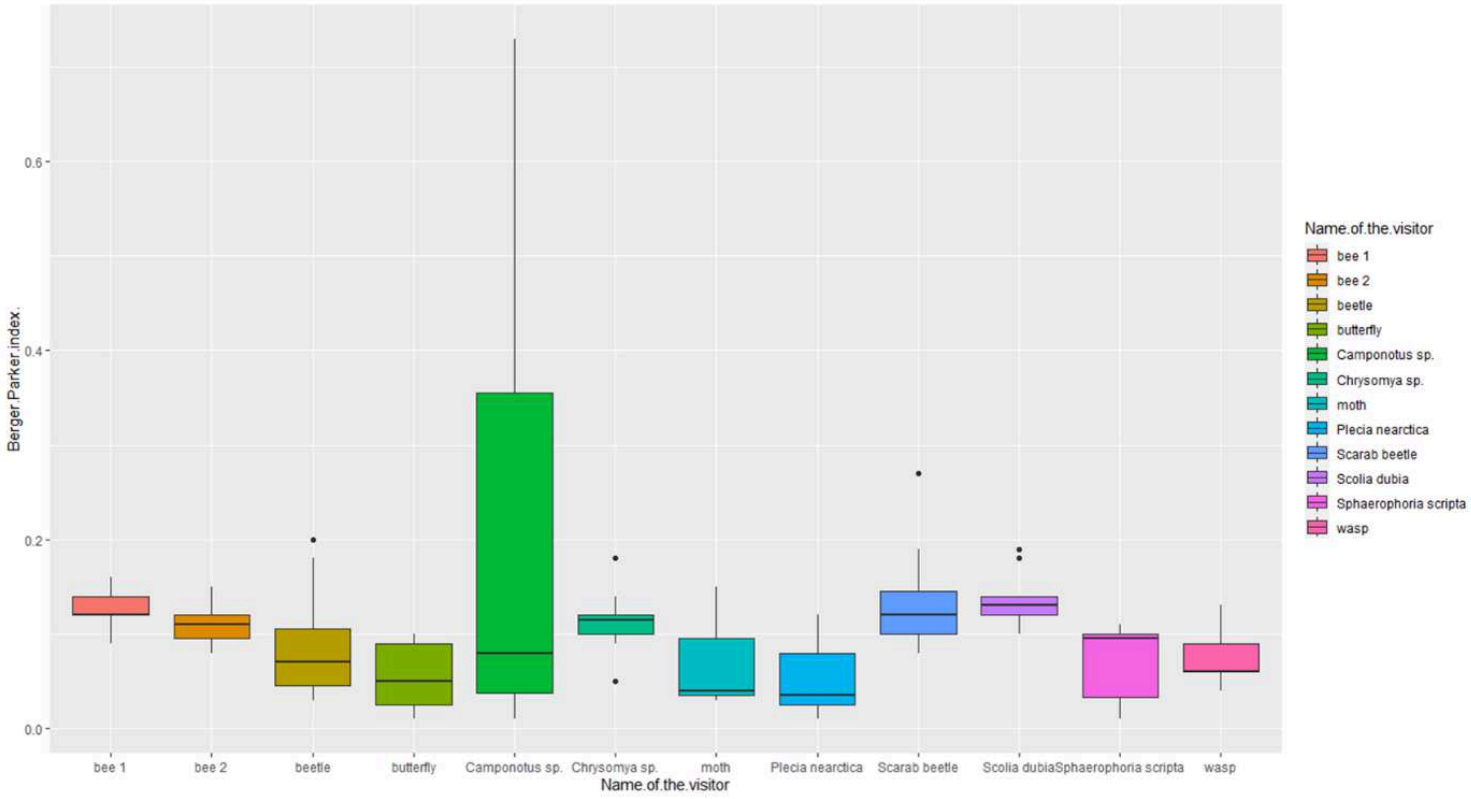


Figure 7

Dominance of floral visitors on the flowers of *S. parameswaranii*

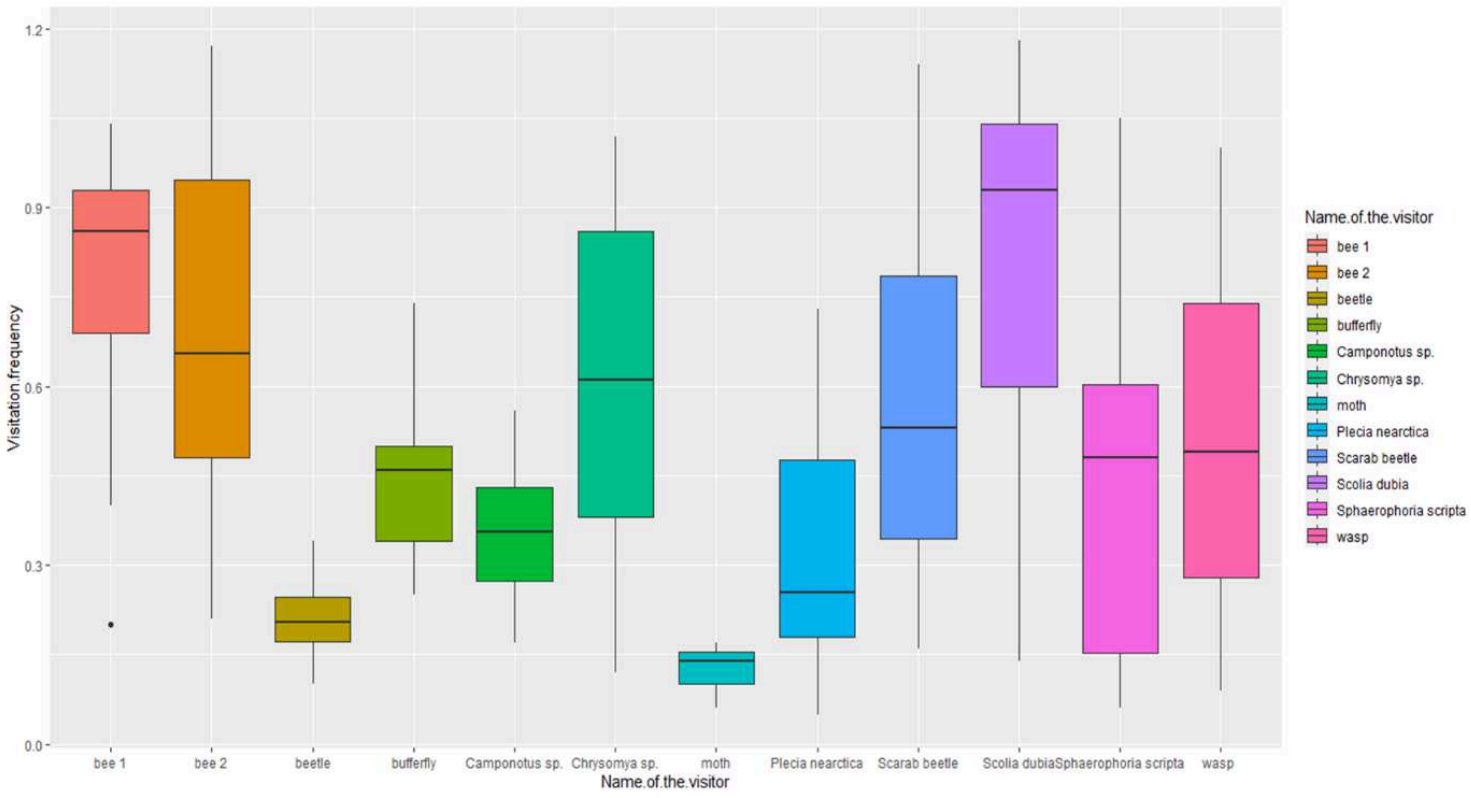


Figure 8

Visitation frequency of various floral visitors on the flowers of *S. parameswaranii*

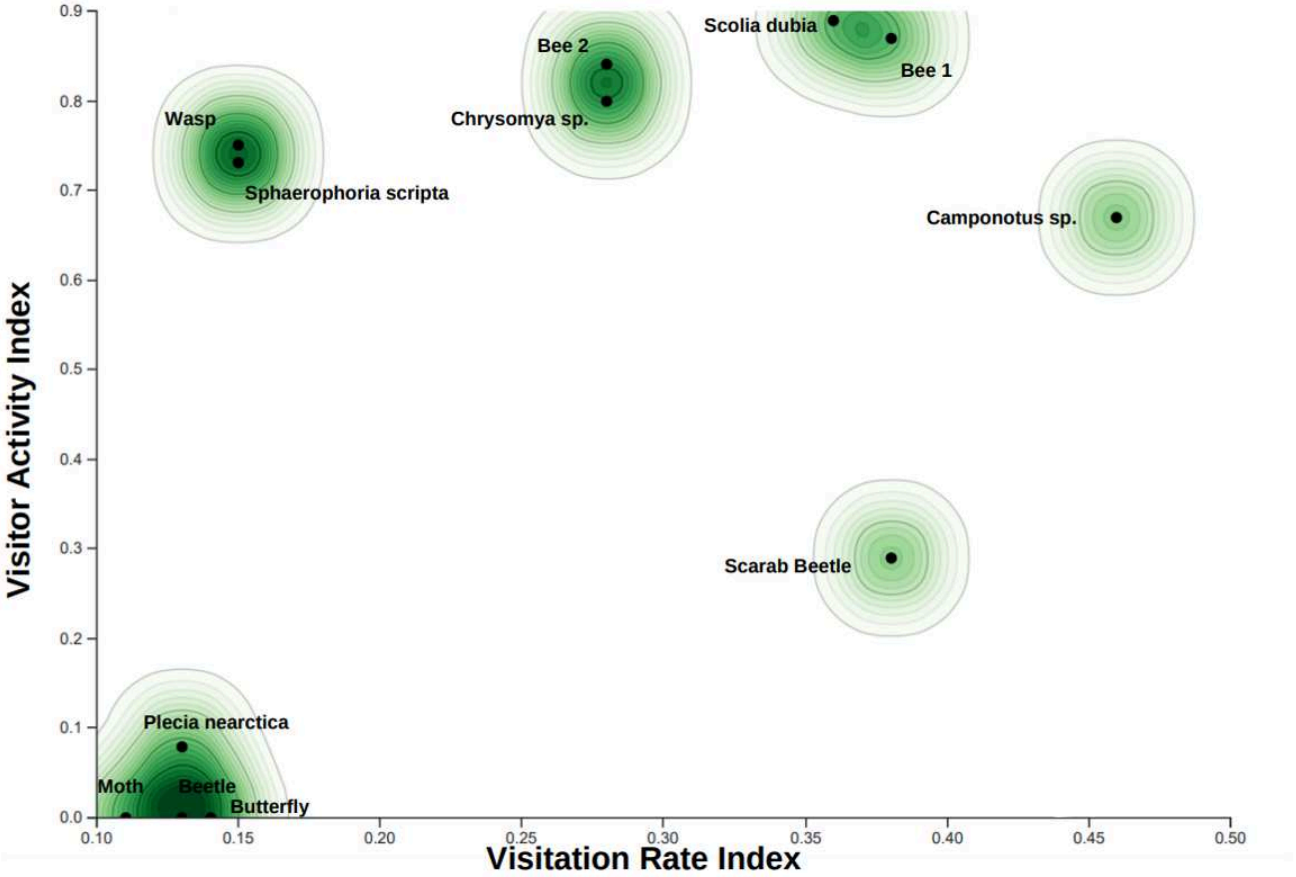


Figure 9

Visitation rate index and visitor activity index of floral visitors of *S. parameswaranii*

Supplementary Files

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