PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–08
https://doi.org/10.14719/pst.5166

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RESEARCH ARTICLE

Weather driven pollination efficiency and foraging activity of stingless bee, *Tetragonula iridipennis* Smith in chilli, *Capsicum annum*

B Saai Vignesh[1], J Jayaraj[1]*, R Nalini[1], K Kumutha[2], MR Srinivasan[1], M Jayakanthan[3] & K Suresh[4]

[1]Department of Agricultural Entomology, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India
[2]Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India
[3]Department of Bioinformatics, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Department of Agricultural Entomology, ICAR-KVK, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India

*Email: jayaraj.j@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 20 September 2024
Accepted: 29 October 2024
Available online
Version 1.0 : 27 December 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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CITE THIS ARTICLE
Saai Vignesh B, Jayaraj J, Nalini R, Kumutha K, Srinivasan M R, Jayakanthan M, Suresh K. Weather driven pollination efficiency and foraging activity of stingless bee, *Tetragonula iridipennis* Smith in chilli, *Capsicum annum*. Plant Science Today.2024;11(sp4):01-08. https://doi.org/10.14719/pst.5166

Abstract

The core objective of this study was to determine suitable pollination methods among stingless bee pollination, open pollination with stingless bee colony and self-pollination, along with the foraging activity of bees in relation to weather influences and their impact on fruit yield and qualities. This investigation was carried out during the Kharif and Rabi cropping seasons using 3 different pollination methods. Bee foraging activity in relation to weather factors was observed at different times of day during the flowering period until the first harvest of chilli fruits and yield attributes were ascertained from all treatments. Results showed that during the Kharif and Rabi cropping seasons, the foraging activity in open pollination supplemented with stingless bee peaked between 1200–1400 h and 1100–1200 h with outgoing bees (28.6 and 25.2 bees/5 min/h), pollen foragers (8.4 and 4.3) and nectar foragers (27.0 and 21.4) respectively. Furthermore, the peak resin foragers (3.7) were observed in Kharif between 1600 – 1700 h and in Rabi (2.3) between 1100–1200 h. In both seasons, all foragers were positively influenced by temperature and wind, whereas negatively influenced by rainfall and relative humidity. Amongst Kharif and Rabi cropping, the yield attributes like the number of flower setting/plant (183.67 ± 11.90 and 177.00 ± 14.76), number of fruit setting/plant (82.67 ± 1.25 and 80.00 ± 0.82) and yield (1099.33 ± 69.93 and 984.20 ± 108.59 kg/ac) were maximum in the open pollination with stingless bee, followed by bee and self-pollination. These findings underscore the significant role of stingless bees in increased chilli production. Detailed foraging behavior in relation to weather factors was studied to inform future crop-specific manageable pollination.

Keywords

chilli yield; foraging activity; pollination impact; *Tetragonula iridipennis*; weather influences

Introduction

In this study, we explore the interaction between stingless bees and chilli plants, focusing on their pollination potential. The stingless bee, *Tetragonula iridipennis*, is a pollinator species, particularly in tropical ecosystems, while the chilli plant (*Capsicum annum*) is one of the most widely cultivated crops, especially in the Solanaceae family, which is rich in vitamins A and C, folic acid, vitamin E and potassium (1). The taxonomic classification of *T.*

iridipennis and *C. annum* is presented in Table 1. Chilli peppers, such as the Bullet Ranga variety, are botanically identified as berries, a type of fleshy fruit that originates from the ovary of a single flower. It originated from Central and South America; the chilli was first cultivated in Peru, where diverse varieties of chilli were grown (2). The major cultivable chilli species worldwide include *C. annum*, *C. chinense*, *C. baccatum*, *C. frutescens* and *C. pubescens* (3). In 2022, the global production of green chilli was estimated at 36.97 million metric tons (4), highlighting their significance in agriculture due to their economic value, widespread culinary use and nutritional value, serving as a rich source of vitamins, capsaicinoids and antioxidants. The major chilli growing areas in India are Andhra Pradesh, Tamil Nadu, Maharashtra, Karnataka, Odisha, Madhya Pradesh and West Bengal. In India, chilli was grown over a vast area of 39000 ha in 2022–23, with a significant output of 601580 metric tons and a productivity rate of 15.40 metric tons per ha (5). Chilli flowers are chasmogamous and self-pollinating, where cross-fertilization occurs at the time of petal opening. The peak visitation frequency of honey bees and other bees on chilli flowers is during warm, bright days or during dry periods (6, 7). Chilli flowers hang downward from leaf axils, featuring a white corolla, up to 7 stamens carrying 1.0 to 1.5 mg of pollen and a single central style with a rounded sticky stigma at its apex. The anthers are tubular and they release pollen over side openings. Flower opening and pollen release both happen in the morning (8). Due to the absence of periodical anthers, buzz pollination is not required for chilli flowers. Even though it is a self-pollination crop, arthropod pollination can enhance crop productivity (9).

Table 1. Taxonomic classification of stingless bee (*Tetragonula iridipennis*) and chilli (*Capsicum annum*).

Taxonomic rank	Stingless bee	Chilli plant
Kingdom	Animalia	Plantae
Phylum	Arthropoda	Magnoliophyta
Class	Insecta	Magnoliopsida
Order	Hymenoptera	Solanales
Family	Apidae	Solanaceae
Genus	*Tetragonula*	*Capsicum*
Species	*Tetragonula iridipennis*	*Capsicum annum*

The biotic and abiotic vectors play a major role in pollination as an ecological service that significantly influences crop productivity. Mostly 80 % of flora depends on arthropods for pollination. Out of that, 90 % of pollination is supported by *Apis*, non-*Apis* bee species of hymenopterans, descended by Diptera, Lepidoptera and Coleoptera (10, 11). In the long run, honey bees show the positive influence of pollinating events (12, 13) and reported that 80 % of pollination was carried out by bees (14). The most primitive and smallest eusocial bee species that produces honey is stingless bees (*T. iridipennis* Smith), which belong to the family Apidae and sub-family Meliponinae. This bee species is most abundant in India, having a high degree of floral fidelity and diversified flora for foraging (15). The stingless bees are the most effective and manageable pollinators in commercial crops of families like Leguminaceae and Cruciferae, etc., where other honey bees fail to pollinate. The efficacy of arthropod pollinators is contingent upon 3 primary factors, *viz*., the contact between the anther stigma of flowers, their capacity for travel and their abundance within the region. The qualitative and quantitative yield of chilli fruits were improved by the arthropod pollinators (16). Agrometeorology, as a discipline, delves into the intricacies of meteorological patterns and leverages weather and climate data to optimize agricultural practices. By harnessing insights from meteorological information, agrometeorology subsidizes the enhancement of agricultural strategies, ultimately leading to increased crop production (17).

Universal food production and crop pollination are at risk due to the declining of pollinator species (18). Climate change and the escalation of agriculture created alarming circumstances against insect pollination and their services (19). Generally, the foraging behavior of honey bees has a notable effect due to temperature and rainfall. Based on findings from previous scientific investigations regarding weather factors and the foraging activity of bees, the present study was performed to investigate the impact of abiotic factors such as temperatures, rainfall, wind speed and relative humidity on the foraging performance of stingless bees and their pollination efficiency in the respective study area cropped with chilli (Fig. 1).

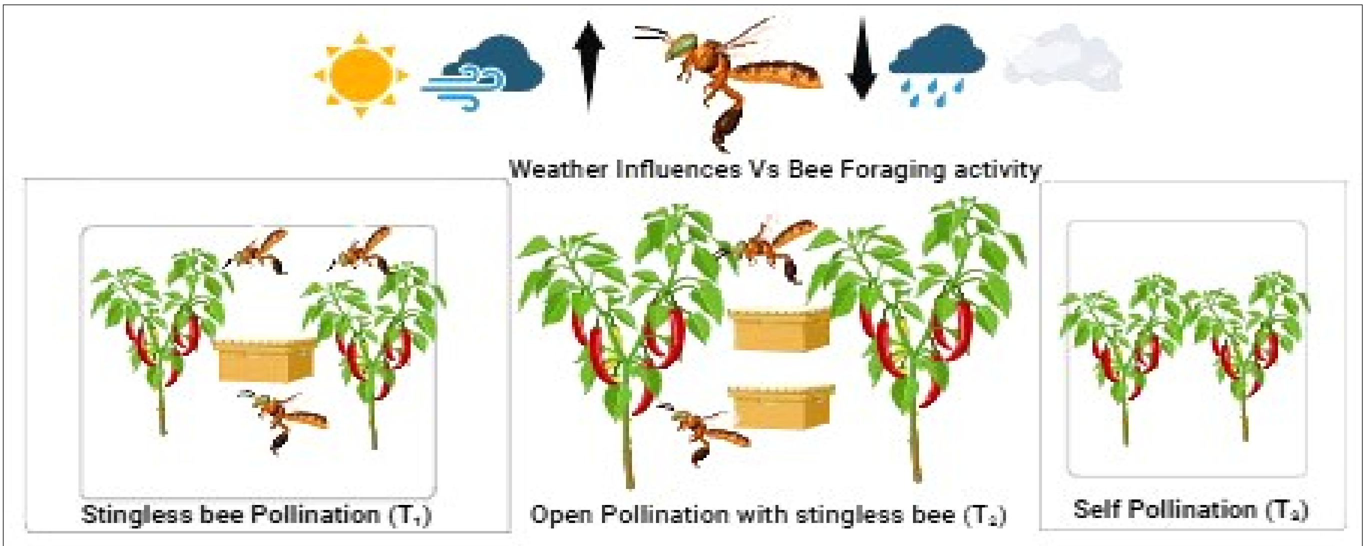

Fig. 1. Influence of abiotic factors on stingless bee foraging activity and pollination efficiency in chilli field.

Materials and Methods

The present investigation with manageable stingless bees' pollination in chilli variety Bullet Ranga was conducted in farmers fields during 2 different seasons, *viz*., Kharif and Rabi at Periyaelandhaikulam (9.970307°N; 78.204831°E), Madurai district of Tamil Nadu, where the standard agronomic practices were followed. The chilli seedlings were transplanted and maintained in an area of one acre from May to August 2023 (Kharif) and November 2023 to February 2024 (Rabi). The experimental field of one acre was selected for the following treatments: (i) stingless bee pollination (T1), (ii) open pollination supplemented with stingless bee colonies (T2) and (iii) self-pollination (T_3).

Field experiments were carried out in randomized block design with 3 replications. For the treatment of stingless bee pollination, a well-developed colony of *Tetragonula iridipennis*, obtained after supplementary feeding, had a colony strength characterized by brood pot volume (82.41 ± 16.79 pots/cu.in), pollen pots (6.88 ± 1.59 pots/cu.in) and honey pots (12.04 ± 2.56 pots/cu.in) (20). This colony was kept in a plot until the first harvest from initial flowering (40 to 45 days) and was fully roofed with nylon net (5 × 3 × 3 m) to evade the other pollinators. For open pollination supplemented with a stingless bee colony, the chilli crops were fully opened and exposed to all pollinators along with the stingless bees by placing 3 colonies/acre. To achieve replication for this treatment, each colony was positioned in the center of a 200 m^2 radius area, considering that the flight range of stingless bee workers is approximately 50 to 500 m (21). This ensured that the chili plants are fully open and exposed to all pollinators. For self-pollination, a plot was fully protected with nylon net (5 × 3 × 3 m) to circumvent the access of pollinators.

With slight modifications, the annotations on the foraging behavior of stingless bees during open pollination were made over a duration of 12 h, from 0700 to 1900 h. Four types of bee foragers and their activities were observed in terms of several worker bees going out and coming in with their rewards for 5 min/h from 0700 to 1900 h in a day at the hive entrance. The key interpretation attributes were recorded at every 3 days intervals during the blooming period. The bees going out to collect floral rewards were designated as outgoing bees, while the incoming bees with pollen and resin in their corbicula were described as pollen and resin foragers respectively. Bees without pollen in their corbicula were described as either nectar or water foragers (22).

The chilli yield characteristics, such as the number of flowers setting/plant, number of fruits setting/plant, fruit size (length and diameter) and fruit yield (kg/ac) were documented to determine the impact of the 3 different methods of pollination treatment (7). We randomly selected 7 plants (n= 7) for each treatment. Each of the 7 plants were considered a replication within individual groups that differed in their method of pollination. The total fruit yield and germination rate of harvested chilli seeds under the 3 different pollination methods were observed. For the germination test, 100 (4 × 25) seeds were taken from 3 different treatment plots and placed on wet germination paper (Roll towel method) at 22–24 °C and the % of germination was recorded (23).

The meteorological data were recorded from the AgroMet Advisory Bulletin (AAB) jointly released by the Regional Meteorology Centre, Chennai – India Meteorology Department, Reddiarchathram Seed Growers Association and M.S. Swaminathan Research Foundation. Following recent studies evaluating the performance of NASA POWER data (24), the requisite hourly weather data for 5 parameters, *viz*., maximum and minimum temperature (°C), rainfall (cm), wind (km/h), relative humidity (%), were obtained from NASA POWER web portal (https://power.larc.nasa.gov/data-access-viewer/). A mean of 12 days was recorded concerning bee foragers from 0700 to 1900 h of the day (Table 2). These factors were also used to

Table 2. Meteorological data in chilli at Periyaelandhaikulam, Alanganallur and Madurai district: Kharif (August to September 2023) and Rabi (December 2023–February 2024).

Time of h	*Weather parameters									
	Maximum temperature (°C)		Minimum temperature (°C)		Rainfall (cm)		Wind (km/h)		Relative humidity (%)	
	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi
0700 to 0800	27.8	23.5	20.8	19.4	0.0	0.4	15.7	10.5	74.0	86.7
0800 to 0900	29.4	24.3	22.3	20.4	0.0	0.3	19.7	12.1	69.6	83.8
0900 to 1000	31.1	25.5	24.1	21.6	0.0	0.2	19.9	13.2	64.8	79.3
1000 to 1100	31.8	26.2	24.8	22.1	0.0	0.2	20.3	13.6	59.8	73.7
1100 to 1200	33.5	28.5	26.5	24.9	0.0	0	21.2	15.3	54.4	68.8
1200 to 1300	34.3	28.9	27.3	25.7	0.0	0.1	18.3	15.1	51.0	66.3
1300 to 1400	35.2	29.3	28.2	26	0.1	0.1	17.3	14.8	45.7	64.1
1400 to 1500	36.5	30.3	29.5	26.7	0.0	0.1	15.3	15	43.3	59.9
1500 to 1600	34.0	30.2	27.0	26.3	0.0	0.3	14.1	14.6	45.6	60.8
1600 to 1700	33.8	29.3	26.8	25.8	0.0	0.2	14.8	13.9	48.2	61.5
1700 to 1800	33.8	27.3	26.8	23.6	0.0	0.4	14.8	13.7	50.3	64.4
1800 to 1900	30.9	26.2	23.9	22.5	0.0	0.4	14.4	12.4	58.2	70.7

Mean of twelve observations of weather data, during chilli flowering period of 2 seasons.

correlate the functional foraging activity of stingless bee, including outgoing bees, pollen, nectar and resin foragers.

The statistical analysis was performed using R Studio with the "agricolae" package for Duncan's Median Range Test (DMRT) to determine the peak foraging time of worker bees. Regression analysis was conducted to predict foraging behavior in relation to changing weather conditions. The "psych" package was used for the correlation matrix, while the "stats" package for ANOVA and Tukey's HSD test (25).

Results and Discussion

Foraging behavior of stingless bee in chilli ecosystem

Chilli flowers naturally faced downward toward the earth. When stingless bees land on an individual flower, they climb to the apex of the anther to gather pollen grains. During this activity, the stingless bees contact the stigma, which results in cross-pollination. Conversely, nectar foragers travel to the base of the flower, bypassing the stigma and focusing on gathering nectar. The stingless bee foragers unveiled notable variations in pollen, nectar, resin collection and outgoing bees' activity on chilli plants across different days and hours (Table 3).

Stingless bee foraging activity in Kharif and Rabi chilli cultivation

Table 3. Foraging activity of *Tetragonula iridipennis* in chilli across Rabi and Kharif seasons.

Time of h	Number of bees*/5 min							
	Outgoing		Pollen carrying		Nectar carrying		Resin carrying	
	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi
0700 to 0800	1.8 (1.34)^{g}	1.1 (0.89)^{g}	0.6 (0.77)^{g}	0.1 (0.0)^{e}	0.9 (0.95)^{g}	0.4 (0.63)^{g}	0.5 (0.71)^{f}	0.3 (0.63)^{d}
0800 to 0900	3.4 (1.84)^{f}	2.3 (1.45)^{f}	0.9 (0.95)^{g}	0.6 (0.63)^{d}	2.3 (1.52)^{f}	1.2 (0.95)^{g}	0.8 (0.89)^{ef}	0.8 (0.84)^{cd}
0900 to 1000	7.3 (2.70)^{e}	6.3 (2.41)^{e}	4.4 (2.09)^{de}	3.0 (1.67)^{bc}	8.1 (2.85)^{d}	7.2 (2.59)^{de}	1.6 (1.26)^{bcd}	1.5 (1.18)^{abc}
1000 to 1100	11.3 (3.36)^{d}	13.1 (3.55)^{bc}	4.8 (2.19)^{cd}	3.2 (1.70)^{bc}	11.8 (3.44)^{c}	10.0 (3.03)^{bcd}	1.3 (1.14)^{cde}	1.1 (1.00)^{bcd}
1100 to 1200	14.6 (3.82)^{c}	25.2 (4.86)^{a}	6.7 (2.58)^{b}	4.3 (2.07)^{a}	23.2 (4.82)^{b}	21.4 (4.40)^{a}	2.1 (1.45)^{bc}	2.3 (1.38)^{a}
1200 to 1300	28.6 (5.34)^{a}	14.6 (3.65)^{b}	5.2 (2.28)^{cd}	4.5 (1.84)^{a}	15.3 (3.91)^{c}	10.8f (3.02)^{bc}	1.3 (1.14)^{cde}	1.5 (1.14)^{abc}
1300 to 1400	22.7 (4.76)^{b}	11.9 (3.35)^{c}	8.4 (2.89)^{a}	3.8 (1.90)^{ab}	27.0 (5.19)^{a}	8.8 (2.77)^{cd}	0.8 (0.89)^{ef}	0.7 (0.77)^{cd}
1400 to 1500	25.3 (5.03)^{b}	15.3 (3.81)^{b}	5.8 (2.41)^{bc}	3.0 (1.64)^{bc}	17.0 (4.12)^{bc}	10.3 (3.15)^{bc}	1.7 (1.30)^{bcd}	1.8 (1.30)^{ab}
1500 to 1600	10.9 (3.30)^{d}	8.3 (2.92)^{d}	4.0 (2.00)^{de}	2.8 (1.64)^{c}	7.7 (2.77)^{d}	5.5 (2.26)^{ef}	1.2 (1.09)^{def}	0.9 (1.05)^{cd}
1600 to 1700	8.2 (2.86)^{e}	5.8 (2.43)^{e}	3.4 (1.84)^{ef}	2.3 (1.52)^{c}	5.5 (2.35)^{e}	3.8 (1.87)^{f}	3.7 (1.92)^{a}	1.9 (1.34)^{ab}
1700 to 1800	13.2 (3.63)^{cd}	12.2 (3.49)^{c}	3.1 (1.76)^{f}	3.2 (1.84)^{bc}	5.0 (2.24)^{e}	11.9 (3.46)^{b}	2.5 (1.58)^{b}	1.5 (1.41)^{abc}
1800 to 1900	0.7 (0.84)^{h}	0.4 (0.63)^{g}	0.8 (0.89)^{g}	0.4 (0.63)^{de}	2.1 (1.45)^{fg}	4.1 (2.10)^{f}	0.8 (0.89)^{def}	0.7 (0.84)^{cd}

No. of bees going out and coming in with rewards for 5 min in an hr. Each value is a mean of twelve observations. Figures in parentheses are square root transformed values; Means followed by same alphabet(s) are on par by DMRT (p=0.05).

The observation of foraging activity of stingless bees during the Kharif season revealed that the peak activity of outgoing bees was observed in the time interval from 1200 to 1300 h, with a mean of 28.6 bees/5 min/h and least activity was recorded between 1800 to 1900 h, with a mean of 0.7 bees/5 min/h. The peak foraging activity of pollen and nectar foragers was recorded between 1300 to 1400 h, with a mean of 8.4 and 27.0 bees/5 min/h and the peak resin foragers was observed between 1600 to 1700 h, with a mean of 3.7 bees/5 min/h. The least activity of bees with nectar, pollen and resin rewards was observed between 0700 to 0800 h. with a mean of 0.9, 0.6 and 0.3 bees/5 min/h respectively. The significant peak of pollen foraging occurred during the noon hours, which was in line with the finding that peak pollen foragers were active at 12 noon (26). However, this finding is inconsistent with other studies that report peak pollen foraging activity occurring in the early morning hours (27, 28). This contradiction might be due to variations in floral rewards availability and microclimate suitability. The results of the present study are also contradictory, as the peak activity of *Tetragonula* sp. was observed from 1000 to 1100 h (29). This discrepancy may be attributed to different agroclimatic factors affecting both the crops and the bees. The maximum number of outgoing bees (88.74 foragers/10 min), pollen (30.55 foragers/10 min), nectar (69.44 foragers/10 min) and resin foragers (5.93 foragers/10 min) were observed during the month of March (27). In line with the previous findings (30), the foraging activity initiated at 0700 h with a rate of 0.70 bees/m^2/10 min and the peak activity of foragers (12.90 bees/m^2/10 min) was observed from 1100 to 1200 h during the summer season.

During the Rabi season, the foraging performance annotations revealed that the maximum number of outgoing bees was recorded in the late morning hours from 1100 to 1200 h, with a mean of 25.2 bees/5 min/h. The least number was observed from 1800 to 1900 h, with a mean of 0.4 bees/5 min/h. Pollen, nectar and resin foragers were found to be enhanced during the late morning hours between 1100 and 1200 h. with means of 4.3, 21.4 and 2.3 bees/5 min/h respectively. In contrast, the least activity of pollen and nectar foragers was noted from 0700 to 0800 h, with means of 0.1 and 0.4 bees/5 min/h respectively. The least foraging performance of resin foragers was also recorded during 0700 to 0800 h, with a mean of 0.3 bees/ 5 min/h. The fallouts of the present investigation are analogous to this result, that the highest outgoing bee activity was observed between 1200 to 1300 h, while peak nectar and pollen foragers were noted during 1300 to 1400 h, coinciding with monsoon weather (31).However, these findings are inconsistent with previous studies that reported peak nectar and pollen foraging activity from 1600 to 1700 h and from 0800 to 0900 h respectively (22). The peak pollen (44.32 bees) and nectar (54.65 bees) foragers were found between 1000 to 1200 h during the months of October to December (32), which were also inconsistent with the present investigation. These inconsistencies may be attributed to changes in weather factors of specific locality. The findings of the current investigation are quite dissimilar to those reported in the previous study (33), where the peak in the number of incoming forager bees (*T. pagdeni*) with and without pollen in the protected cultivation of tomato occurred at 1000 h. The number of bees carrying pollen was 19 ± 2.43, while those without pollen load numbered 44 ± 3.49. These differences may be attributed to greenhouse conditions, where the controlled cropping system has higher temperatures and humidity earlier compared to open field cropping.

Influence of weather factors on stingless bee foragers on chilli

The association between weather factors and foraging activity of *T. iridipennis* during the Kharif season, the temperatures (maximum and minimum), and rainfall showed a high and moderate positive correlation with outgoing bees and incoming foragers with floral rewards. In contrast, wind speed exhibited a low positive correlation with outgoing bees, as well as pollen and nectar foragers; however, it was negatively correlated with resin foragers. Relative humidity demonstrated a moderate negative correlation with bee foragers. The results of Rabi season, revealed that the temperatures and wind speed showed a moderate positive correlation to the outgoing and incoming foragers with rewards. However, the relative humidity and rainfall exhibited a moderate negative correlation with the foragers going out and coming in (Table 4) (Fig. 2). These results are inconsistent with the findings, which observed that stingless bees had weak negative and weak positive correlation with maximum temperature as r = −0.24 and r = +0.01 respectively. They also showed a moderate negative correlation with minimum temperature (r = −0.69) and had a weak negative correlation with wind speed (r = −0.07) (34). Nevertheless, relative humidity and rainfall showed negative correlations of r = −0.35 and r = −0.40 respectively, which are analogous to our investigation. These incomparable results might be due to seasonal variations between the study locations. Bee foragers in the cucumber field showed a significant positive correlation with temperature (r = + 0.78) and a negative correlation with relative humidi-

Table 4. Correlation between weather factors and foraging activity of *Tetragonula iridipennis* in chilli.

Weather parameters	Kharif season				Rabi season			
	Outgoing bees	Pollen foragers	Nectar foragers	Resin foragers	Outgoing bees	Pollen foragers	Nectar foragers	Resin foragers
Maximum temperature	+0.83	+0.77	+0.68	+0.43	+0.57	+0.67	+0.46	+0.52
Minimum temperature	+0.83	+0.77	+0.44	+0.44	+0.57	+0.68	+0.47	+0.52
Wind	+0.10	+0.32	+0.14	−0.14	+0.81	+0.90	+0.74	+0.67
Relative humidity	−0.71	−0.65	−0.44	−0.44	−0.48	−0.60	−0.42	−0.49
Rainfall	+0.36	+0.57	+0.25	−0.25	−0.78	−0.76	−0.67	−0.64

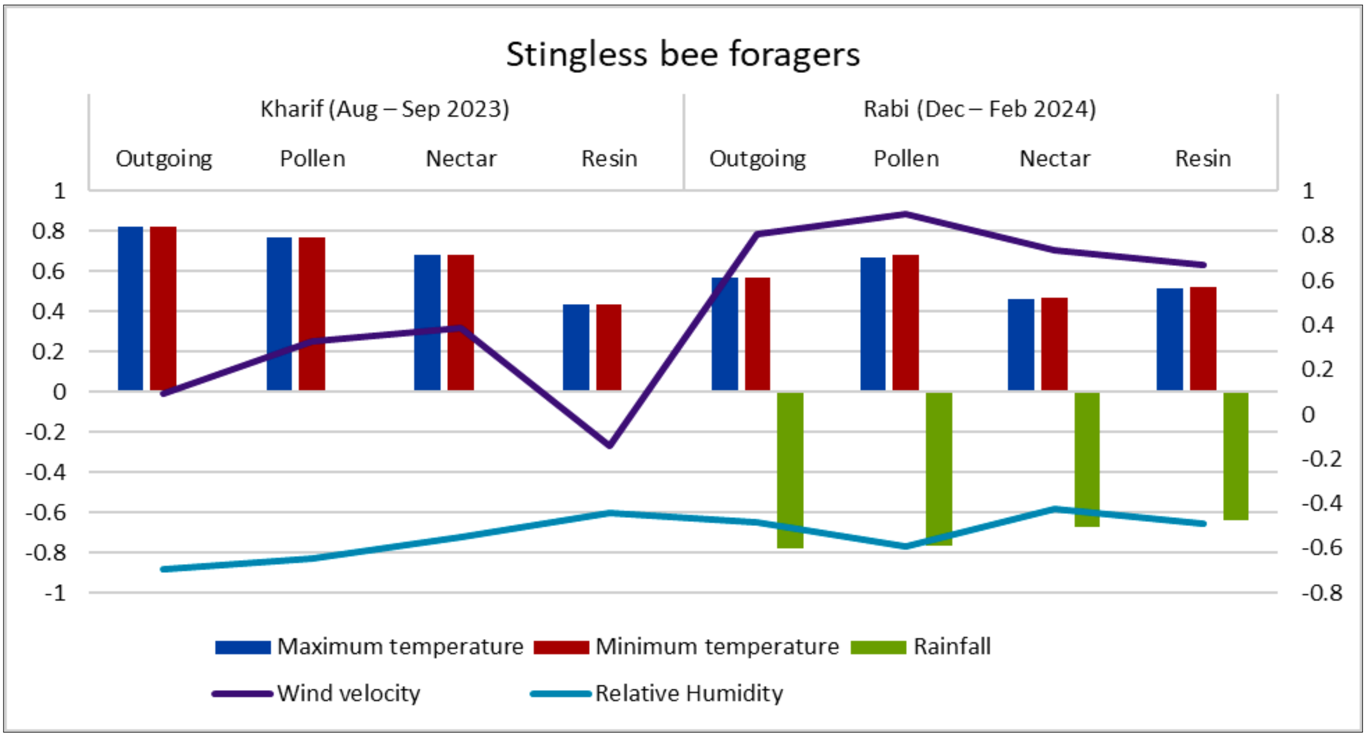

Fig. 2. Correlation matrix between weather parameters and foraging activity of *Tetragonula iridipennis* in chilli.

ty (r = –0.68) (35), which is in line with the present investigation. The fallouts of the present investigation were tangential to the previous findings (33), that the number of outgoing and incoming foragers in tomato cropping declined at noon (1100 to 1200 h), while the humidity and temperature were 73.84 % and 32.0 °C inside the greenhouse. The differences in peak foraging hours might be due to the influence of weather factors in open and controlled field conditions. As the greenhouse attains high temperature and humidity earlier than the natural cropping environments, this could affect foraging behavior.

Predicting foraging activity based on weather

Multiple regression analysis illustrated how each weather parameter contributed to the foraging activity of stingless bees. The relationship between foraging activity and weather factors during the Kharif season indicated that maximum temperature had a negative regression coefficient for outgoing foragers (a = –6.87), pollen collectors (a = –20.89), nectar foragers (a = –52.73) and resin foragers (a = –2.43). In contrast minimum temperature depicted positive regression coefficient for outgoing bees (b= +15.40), pollen foragers (b = +21.55), nectar foragers (b = +55.07) and resin foragers (b = +2.42) during August to September 2023. Manageable stingless bee pollination during the Kharif season illustrated that a 10 °C increase in maximum temperature would lead to a decrease of 6.87 outgoing bees, 20.89 pollen foragers, 52.73 nectar foragers and 2.43 resin collectors.

During the Rabi season, the maximum temperature depicted positive regression coefficient for outgoing bees (a = +2.97) and resin foragers (a = +0.01), while it showed negative regression coefficient for pollen foragers (a = –0.52) and nectar collectors (a = –1.12). The minimum temperature displayed negative regression coefficient for outgoing bees (b = –6.35), nectar collectors (b = –3.55) and resin foragers (b = –0.43), but a positive regression coefficient for pollen foragers (b= +0.08) during December to February (Table 5). Pollination during the Rabi season by stingless bees clearly depicted that a 1°C increase in maximum temperature would lead to an increase of 2.97 in outgoing bees, an increase of 0.01 in pollen foragers and decreases of 0.52 and 1.12 in pollen and nectar collectors respectively. This pattern is similarly observed with other weather parameters as well. This prediction was in line with findings that the number of bees going out for forage was negatively influenced by maximum temperature (r = –0.72) (36). It is also analogous to the finding that both maximum and minimum temperatures had a positive influence on the outgoing and pollen foragers of stingless bees (34). Furthermore, this prophecy was comparable with the finding that the activity of stingless bee foraging was lower in winter months, as the flight activity reduced when compared to warmer days (37, 38).

Yield attributes of chilli fruits

In the chilli field during the Kharif and Rabi seasons, open pollination with the presence of stingless bee colonies showed significant yield qualities among different pollinating methods, such as number of flowers setting/plant (183.67 ± 11.90 and 177.00 ± 14.76), number of fruits setting/plant (82.67 ± 1.25 and 80.00 ± 0.82), fruit length (6.76 ± 1.47 and 6.33 ± 0.86) and diameter (1.81 ± 0.10 and 1.70 ± 0.20) respectively and followed by the treatment with caged bee pollination and self-pollination. This finding aligns with previous research indicating that yield attributes and chilli yield were significantly higher in natural pollination, followed by bee pollination (7).

A plot with the existence of a stingless bee colony during the Kharif and Rabi seasons yielded a fruit harvest of 1099.33 ± 69.93 and 984.20 ± 108.59 kg/ac respectively. In contrast, the plot under the exclusion of pollinator yielded about 958.00 ± 108.59 and 888.00 ± 96.61 kg/ac respectively (Table 6). This indicates a 14.71 % and 10.81 % increase in seed yield due to stingless bee manageable pollination in the Kharif and Rabi seasons respectively. The results are incomparable with the outcome that in onion crop, pollination by bees (93.24 ± 2.48) showed a higher percentage of fruit set in crops than open pollination (92.14 ± 2.43), hand pollination (70.60 ± 3.36) and self-pollination (5.44 ± 1.23) (22). Additionally, it aligns with finding that showed a 31% increase in seed production of coriander in stingless bee manageable pollination (39). There was a 25.74 % increase in bee pollination yield compared to mechanical pollination (40), which aligns with this finding. The germination rate (mean value of 100 seeds) of chilli seeds harvested from Kharif and Rabi cropping shows the highest rates in open pollination with a stingless bee at 87 and 85 % respectively (Table 6). This finding is consistent with the outcome that there has been a signifi-

Table 5. Multiple linear regression equations for foraging performance of stingless bees with weather parameters during Kharif and Rabi season, 2023–2024.

Cropping seasons	Type of foragers	Multiple regression equation	R^2 values
Kharif	Outgoing bees	$Y = -236.98 - 6.87 X_1 + 15.40 X_2 - 0.18 X_4 + 1.47 X_5$	0.83
	Pollen	$Y = 125.61 - 20.89 X_1 + 21.55 X_2 + 0.53 X_4 - 0.02 X_5$	0.88
	Nectar	$Y = 288.69 - 52.73 X_1 + 55.07 X_2 + 1.92 X_4 - 0.03 X_5$	0.77
	Resin	$Y = 20.46 - 2.43 X_1 + 2.42 X_2 + 0.02 X_4 - 0.04 X_5$	0.20
Rabi	Outgoing bees	$Y = 51.55 + 2.97 X_1 - 6.35 X_2 - 22.03 X_3 + 5.08 X_4 - 0.54 X_5$	0.81
	Pollen	$Y = -6.01 - 0.52 X_1 + 0.08 X_2 + 0.02 X_3 + 1.53 X_4 - 0.01 X_5$	0.88
	Nectar	$Y = 102.46 - 1.12 X_1 - 3.55 X_2 - 16.56 X_3 + 5.29 X_4 - 0.69 X_5$	0.78
	Resin	$Y = 18.12 + 0.01 X_1 - 0.43 X_2 - 3.82 X_3 + 0.09 X_4 - 0.11 X_5$	0.59

X1 - Maximum temperature; **X2** - Minimum temperature; **X3** - Rainfall; **X4** - Wind velocity; **X5** - Relative humidity.

Table 6. Yield attributing characters and yield of chilli.

Season	Treatment	Number of flowers setting/plant	Number of fruits setting/plant	Length of fruit (cm)	Fruit diameter (cm)	Fruit yield (kg/ac)	Germination (%)
Kharif	T_1	176.00 ± 15.12^b	81.33 ± 1.70^a	7.63 ± 1.47^a	2.11 ± 0.11^a	1099.33 ± 69.93^{ab}	85
	T_2	183.67 ± 11.90^a	82.67 ± 1.25^a	6.76 ± 1.47^{ab}	1.81 ± 0.10^b	1216.67 ± 84.98^a	87
	T_3	148.33 ± 14.70^c	74.67 ± 4.03^b	5.45 ± 1.71^b	1.57 ± 0.08^c	958.00 ± 108.59^b	81
Rabi	T_1	165.67 ± 13.42^b	78.67 ± 0.47^a	7.10 ± 1.17^a	2.02 ± 0.10^a	984.20 ± 108.59^{ab}	83
	T_2	177.00 ± 14.76^a	80.00 ± 0.82^a	6.33 ± 0.86^{ab}	1.70 ± 0.20^b	1115.00 ± 87.27^a	85
	T_3	150.33 ± 12.04^c	71.67 ± 2.49^b	5.19 ± 0.77^b	1.35 ± 0.09^c	888.00 ± 96.61^b	80

T_1 - Stingless bee pollination; **T_2** - open pollination supplemented with stingless bee colony; **T_3** - self-pollination, *values are mean of three replications given as average ± standard deviation. Means in the column followed by the same letter(s) do not differ significantly at 5 % level by Tukey's HSD test.

cant increase in the germination rate of uncaged inflorescences (23). Inadequate pollen deposition leads to low-quality fruit. Even in self-pollinating crops, a lack of sufficient pollen on the stigma can cause pollination deficiency. Bee pollination enhances pollen transfer more effectively than self-pollination (41).

Conclusion

This study highlights the significant role that climatic factors play in the foraging behaviour of stingless bees on chilli plants. While weather conditions such as rainfall and high humidity were found to reduce foraging activity, the strategic hiving of stingless bee colonies in chilli fields greatly enhanced pollination efficiency. As a result, this approach not only improved the yield of chilli fruits but also positively impacted their quality. These findings suggest that integrating stingless bees into chilli cultivation can be an effective strategy for boosting both productivity and crop quality, even under varying climatic conditions.

Acknowledgements

We would like to express gratitude to Tamil Nadu Agricultural University for funding this research through the "VCS-V60JY" scheme and the Department of Agricultural Entomology. Heartful thanks to the farmers who helped by providing cropped areas of chilli for this research work.

Authors' contributions

BSV developed the research questions and designed the experimental setup, data collection methods, data analysis and drafted the manuscript. JJ, RN and MRS served as the advisor for the research work, data analysis and drafting of the manuscript. KK and MJ performed the manuscript drafting. KS contributed by planning the selection of the research field. Hence, the authors equally contributed towards the experiments. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Marín A, Ferreres F, Tomás-Barberán FA, Gil MI. Characterization and quantitation of antioxidant constituents of sweet pepper (*Capsicum annuum* L.). J Agric Food Chem. 2004 Jun 16;52(12):3861-69. https://doi.org/10.1021/jf0497915
2. Meckelmann SW, Riegel DW, Van Zonneveld MJ, Ríos L, Peña K, Ugas R, et al. Compositional characterization of native Peruvian chili peppers (*Capsicum* spp.). J Agric Food Chem. 2013 Mar 13;61(10):2530-37. https://doi.org/10.1021/jf304986q
3. Nasrin M, Amin MR, Miah MR, Akanda AM, Miah MG. Impact of foraging insect pollinators on chili production. Bangladesh J Agril Res. 2021 Sep;46(3):297-306.
4. Food and Agriculture Organization. FAOSTAT database. FAO; 2023. Available from: https://www.fao.org/faostat/en/#data/QCL
5. Indiastat. Area production and yield of capsicum in India (2011-12 to 2022-23-2nd advance estimates) [Internet]. Indiastat.com; 2023. Available from: https://www.indiastat.com/table/capsicum/area-production-yield-capsicum-india-2011-2012-202/962295
6. Chadha ML, Gniffke PA. International scenario on research and development in chillies. In: Kumar R, Rai AB, Singh HP, editors. Advances in Chilli Research. New Delhi: Studium Press; 2010.p.51-86.
7. Vishwakarma R, Singh R. Insect pollinators and their pollinating efficiency on fruit yield of chilli. Adv Biores. 2018;9(6):124-29. https://doi.org/10.15515/abr.0976-4585.9.6.124129
8. Dag A, Kammer Y. Comparison between the effectiveness of honey bee (*Apis mellifera*) and bumble bee (*Bombus terrestris*) as pollinators of greenhouse sweet pepper (*Capsicum annuum*). Am Bee J. 2001;141:447-48.
9. Chauhan A, Imtinaro L. Impact of bee pollination on chilli, *Capsicum annum* under the low-hill conditions of Nagaland. Int J Farm Sci. 2024;14(1&2):64-69. https://doi.org/10.5958/2250-0499.2024.00027.X
10. Aizen MA, Aguiar S, Biesmeijer JC, Garibaldi LA, Inouye DW, Jung C, et al. Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. Glob Change Biol. 2019 Oct;25(10):3516-27. https://doi.org/10.1111/gcb.14736
11. Rader R, Cunningham SA, Howlett BG, Inouye DW. Non-bee insects as visitors and pollinators of crops: Biology, Ecology and Management. Annu Rev Entomol. 2020 Jan 7;65(1):391-407.
12. Layek U, Kundu A, Bisui S, Karmakar P. Impact of managed stingless bee and western honey bee colonies on native pollinators and yield of watermelon: A comparative study. Ann Agri Sci. 2021 Jun 1;66(1):38-45. https://doi.org/10.1016/j.aoas.2021.02.004
13. Nkoba K, Maria IP, Annette VO, Junior K, Felix W, Frank VL, et al. Effective pollination of greenhouse Galia musk melon (*Cucumis*

melo L. var. *reticulatus* ser.) by Afrotropical stingless bee species. J Environ Health. 2022. https://www.tandfonline.com/doi/full/10.1080/00218839.2021.2021641

14. Food and Agriculture Organization. Why bees matter: The important of bees and other pollinators for food and agriculture. Ministry of Agriculture, Forestry and Food, Slovenia; 2018
15. Layek U, Karmakar P. Nesting characteristics, floral resources and foraging activity of *Trigona iridipennis* Smith in Bankura district of West Bengal, India. Insectes Soc. 2018 Feb;65:117-32. https://doi.org/10.1007/s00040-017-0593-4
16. Aminatun T, Sugiyarto L, Setyawan SA, Desiliani A. The effect of pollinator insect visitation on flower development and productivity of chilli plant. J Phys Conf Ser. IOP Publishing. 2019 Nov 1;1387(1):012002. https://doi.org/10.1088/1742-6596/1387/1/012002
17. Frere M. Overview of agrometeorology. Satellite remote sensing applications in agroclimatology and agrometeorology. In: Proceedings of the Joint ESA/FAO/WMO International Training Course held 2-13 October, 1978 in Rome, Italy. Edited by EC Barrett. ESA SP-1020. European Space Agency; 1979.1020(3): p.3.
18. Gallai N, Salles JM, Settele J, Vaissière BE. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecol Econ. 2009 Jan 15;68(3):810-21. https://doi.org/10.1016/j.ecolecon.2008.06.014
19. Klein AM, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, Tscharntke T. Importance of pollinators in changing landscapes for world crops. Proc Royal Soc Biol Sci. 2007 Feb 7;274(1608):303-13. https://doi.org/10.1098/rspb.2006.3721
20. SaaiVignesh B, Jayaraj J, Nalini R, Kumutha K, Srinivasan MR, Jayakanthan M, Suresh K. Impact of artificial pollen diet on colony productivity in stingless bee, *Tetragonula iridipennis* (Smith) (Hymenoptera: Apidae) during dearth period. J Xidian Univ. 2024;18(6):247-53. https://doi.org/10.5281/zenodo.11488836
21. Putra RE, Kinasih I. Efficiency of local Indonesia honey bees (*Apis cerana* L.) and stingless bee (*Trigona iridipennis*) on tomato (*Lycopersicon esculentum* Mill.) pollination. Pak J Biol Sci. 2014;17(1):86-91. https://doi.org/0.3923/pjbs.201.86.91
22. Divija SD, Kamala Jayanthi PD. Pollination efficiency and foraging behaviour of honey bees and flies to onion *Allium cepa* L. J Apic Res. 2022 Oct 20;61(5):688-94. https://doi.org/10.1080/00218839.2022.2096305
23. Benedek P, Gaal E. The effect of insect pollination on seed onion, with observations on the behaviour of honeybees on the crop. J Apic Res. 1972 Jan 1;11(3):175-80. https://doi.org/10.1080/00218839.1972.11099720
24. Rodrigues GC, Braga RP. Evaluation of NASA POWER reanalysis products to estimate daily weather variables in a hot summer mediterranean climate. Agron. 2021 Jun 14;11(6):1207. https://doi.org/10.3390/agronomy11061207
25. Chambers JM. Software for data analysis: programming with R. New York: Springer; 2008 Jun 14. https://doi.org/10.1007/978-0-387-75936-4
26. Danaraddi CS. Studies on stingless bee, *Trigona iridipennis* smith with special reference to foraging behaviour and melissopalynology at Dharwad, Karnataka. Doctoral Dissertation, UAS , Dharwad.2007.
27. Rakshitha TN. Stingless bee, *Tetragonula iridipennis* as a pollinator in Bell pepper, *Capsicum annum* under protected cultivation. Res Sq. 2024;1-8.
28. Vijayan M, Saravanan PA, Srinivasan MR. Effect of season and timings on the foraging behaviour of stingless Bee, *Tetragonula iridipennis* Smith (Hymenoptera: Apidae). Madras Agric J. 2018 Aug 14;105(7-9):286-90. https://doi.org/10.29321/MAJ.2018.000147
29. Wongsa K, Duangphakdee O, Rattanawannee A. Pollination efficacy of stingless bee, *Tetragonula pagdeni* Schwarz (Apidae: Meliponini), on greenhouse tomatoes (*Solanum lycopersicum* Linnaeus). PeerJ. 2023 May 5;11:e15367. https://doi.org/10.7717/peerj.15367
30. De Bruijn LL, Sommeijer MJ. Colony foraging in different species of stingless bees (Apidae, Meliponinae) and the regulation of individual nectar foraging. Insectes Soc. 1997 Mar;44:35-47. https://doi.org/10.1007/s000400050028
31. Attigeri SG, Kandakoor SB, Kambrekar DN, Hiremath SM. Comparative pollination studies using *Apis cerana indica* and *Tetragonula iridipennis* in onion (*Allium cepa* L.) seed production. App Ecol Environ Res. 2024 Jan 1;22(1). http://dx.doi.org/10.15666/aeer/2201_175190
32. Roopa AN, Eswarappa G, Sajjanar SM, Gowda G. Study on identification of pasturage sources of stingless bee (*Trigona iridipennis* Smith). Int J Curr Microbiol Appl Sci. 2017;6:938-43.
33. Mythri PG, Kencharaddi RN, Venukumar S, Hanumantharaya L, Shivaprasad M, Hosagoudar GN. Foraging behaviour of stingless bee, *Tetragonula iridipennis* (Smith). JExp Zool India. 2023 Jan 1;26(1). https://doi.org/10.51470/jez.2023.26.1.461
34. Bharath MP, Chinniah C, Jayaraj J, Suresh K, Balamohan TN, Vellaikumar S. Foraging activity of stingless bee, *Tetragonula iridipennis* smith (Hymenoptera: Apidae) during summer season in Madurai district of Tamil Nadu, India. J Pharmacogn Phytochem. 2020;9(1):1144-48.
35. Lintu VV. Foraging behaviour of *Tetragonula iridipennis* (Smith) in cucumber under protected cultivation. Int J Agric Sci. 2020;12(18):10227-30.
36. Reddy PR, Rashmi T, Verghese A. Foraging activity of Indian honey bee, *Apis cerana* in relation to ambient climate variables under tropical conditions. J Environ Biol. 2015 May 1;36(3):577.
37. Hilário SD, Ribeiro MD, Imperatriz-Fonseca VL. Can climate shape flight activity patterns of *Plebeia remota* Hymenoptera, Apidae)?. Iheringia Sér Zool. 2012;102:269-76. https://doi.org/10.1590/S0073-47212012000300004
38. de Figueiredo-Mecca G, Bego LR, do Nascimento FS. Foraging behavior of *Scaptotrigona depilis* (Hymenoptera, Apidae, Meliponini) and its relationship with temporal and abiotic factors. Sociobiology. 2013 Nov 6;60(3):267-82. https://doi.org/10.13102/sociobiology.v60i3.267-282
39. SaaiVignesh B, Anujaa B, Manickavasagam S. Pollination efficiency and foraging activity of stingless bee (*Tetragonula "iridipennis"* sp. group) in open field coriander cropping. JAppl Hortic. 2024 Jan 1;26(1). https://doi.org/10.37855/jah.2024.v26i01.07
40. Martinovski Đ, Jankulovski D, Agić R. Analysis of onion (*Allium cepa* L.) seed yield components depending on the pollination method. Sel Semen. 1997;4,165-69.
41. MacInnis G, Forrest JR. Field design can affect cross-pollination and crop yield in strawberry (*Fragaria x ananassa* D). Agric Ecosyst Environ. 2020 Feb 15; 289:106738. https://doi.org/10.1016/j.agee.2019.106738