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Effectiveness of infrared sensor camera monitoring for detecting pollinator visits to *Cremastra appendiculata* var. *variabilis* in a temperate forest in Central Japan

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Abstract

Pollination is one of the most crucial plant–animal interactions. Although direct observation, continuous video recordings, scheduled cameras, and other strategies are often used to monitor flower visitors, long-term observation remains challenging, especially at night. In this study, we evaluated the effectiveness of a commercially available infrared sensor camera (Ltl-Acorn 6210) in detecting pollinator visits to *Cremastra appendiculata* var. *variabilis*, a forest orchid with a highly specialized pollination system. Over 4 years (2019–2022), 151 cameras were deployed across 151 inflorescences, yielding 2707 camera days and 885 videos of *Bombus diversus* queens, the only insect observed with attached pollinia. Fruit development occurred only at inflorescences where *B. diversus* queen visits were recorded, and pollinia removal was observed almost exclusively at such inflorescences, confirming that the sensor camera successfully detected visits contributing to pollination success. Other insects, including *B. ardens*, Syrphinae flies, and nocturnal moths contacted the flowers, but did not carry pollinia. Sensor cameras recorded visits successfully even during warm daytime hours, likely due to the high thoracic temperatures of bumblebee queens. Compared to scheduled cameras, sensor cameras produced fewer invalid recordings and more detections. However, a limitation was that small heterothermic insects were rarely detected. Our findings show that sensor cameras are a reliable, low-maintenance tool for long-term monitoring of effective pollinators in forest ecosystems. While not suited to comprehensive pollinator network studies, they are valuable for detecting large-bodied insects, enabling efficient, long-duration monitoring.

KEYWORDS

bumblebee queen, camera trap, forest floor, orchid pollination, pollinator monitoring

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1 | INTRODUCTION

Pollination represents one of the most crucial plant–animal interactions, with up to 87.5% of terrestrial angiosperms relying on animals for pollination (Ollerton et al., 2011). Insects dominate the pollinator community, with Lepidoptera, Coleoptera, Hymenoptera, and Diptera making up 98% of recorded pollinators (Ollerton, 2017). When a single plant species is serviced by multiple effective pollinator species—driven by high species diversity and functional complementarity among pollinators (Albrecht et al., 2012; Fründ et al., 2013)—the flower–pollinator interactions can be more complex than previously assumed, warranting detailed observation. Concurrently, concerns over pollinator declines due to climate change and habitat loss raise questions regarding potential impacts on the reproduction of wild plants and on agricultural productivity (Thomann et al., 2013). These trends underscore the urgent need for more accurate and effective documentation of plant–pollinator interactions.

Flower-visiting animals have traditionally been observed directly by human observers. Camera-based observation methods are increasingly recognized as a non-invasive approach for monitoring the rapidly declining pollinator abundance and species richness (Høye et al., 2025). Conventional methods such as continuous video recording (Lahondere et al., 2020), scheduled cameras (Alison et al., 2022; Naqvi et al., 2022), and DIY systems (Droissart et al., 2021; Pegoraro et al., 2020; Steen, 2017; van Klink et al., 2024), allow for automated monitoring without human presence. However, these methods often face logistical challenges, particularly regarding data efficiency and monitoring duration. Continuous video and scheduled interval recording generate large volumes of irrelevant footage (i.e., empty frames without visitors), making data storage and analysis time-consuming and labor-intensive. Furthermore, the high-power consumption and storage requirements of continuous recording limit the deployment period (Naqvi et al., 2022; Pegoraro et al., 2020), which can be problematic for capturing infrequent visitors or monitoring throughout the entire flowering season. While DIY systems offer customization, they often entail technical complexity in assembly and programming (Droissart et al., 2021). These limitations—especially the trade-off between monitoring duration and data volume—have prompted growing interest in sensor cameras as a more efficient and reliable alternative.

Sensor cameras are particularly promising for long-term ecological monitoring due to their passive, automated operation. They automatically record animal visits as still images or videos and have been widely used in wildlife research (O'Connell et al., 2011; Smith et al., 2020). Their low power consumption allows extended deployment (Apps & McNutt, 2018; O'Connell et al., 2011), making them suitable for detecting rare events such as seed dispersal (Burton et al., 2015). Although their effectiveness declines in warm environments or when temperature differences between the background and the object are small (Hobbs & Brehme, 2017; Yamada & Ando, 2015), sensor cameras have successfully captured flower visits by birds and mammals in pollination ecology (Krauss et al., 2018). In very recent years, sensor cameras have been applied to studies of insect pollination and shown to capture relatively large flower-visiting insects (Johnson, 2024a; 2024b; 2024c; Johnson & Balducci, 2024; Shaw-Bonner et al., 2023). However, their detection efficiency and reliability in confirming pollination events remain insufficiently validated under field conditions. Importantly, because many pollination events are rare, occur at night, or involve unexpected pollinator taxa, long-term monitoring is often required to detect them. Recent studies have demonstrated the utility of sensor cameras in revealing such overlooked pollination interactions. For example, van der Niet et al. (2022) used long-term sensor camera monitoring of an orchid species to reveal an unexpected sunbird pollinator. These findings highlight the potential of sensor cameras to uncover interactions that occur at night or involve unexpected species.

Many orchid species require pollinators for reproduction. For instance, Ackerman et al. (2023) estimated that 81% of 2466 orchid species in their database received pollinator services, and 76% were entirely dependent on pollinators for reproduction. Orchid pollen forms cohesive masses termed pollinia, which contain many pollen grains. The removal of pollinia from a flower provides direct evidence of a pollinator visit (Suetsugu & Tanaka, 2013), making orchids a suitable model for evaluating the effectiveness of sensor cameras in detecting pollination events. Previous studies identified the queen of *Bombus diversus* as the only pollinator of the perennial orchid *Cremastra appendiculata* var. *variabilis* (Sugiura, 1996). However, flower visits by queens are infrequent: in one study, only four were recorded during 22.75 h of direct daytime observation (Sugiura, 1996). In addition, *C. appendiculata* var. *variabilis* has a long flowering period of more than a week (Zhang et al., 2010) and continues to bloom at night. These traits make it an ideal candidate for sensor camera monitoring, which allows continuous, noninvasive observation across day and night.

In this study, we evaluated the effectiveness of sensor camera monitoring for detecting pollinator visits to *C. appendiculata* var. *variabilis*. Specifically, this study had three main objectives. First, we tested whether the known pollinator, *Bombus diversus* queens (Sugiura, 1996), could be reliably detected by the sensor camera. Second, we

examined whether extended monitoring, including nighttime observations, could reveal additional floral visitors that might have been overlooked in previous studies. Third, we assessed whether camera-detected visits can serve as a reliable proxy for pollination success, under the assumption that *B. diversus* queens remain the only effective pollinators. To address these objectives, we compared the sensor camera's performance with that of a scheduled time-lapse camera and evaluated the correspondence between recorded visits and reproductive success including pollinia removal and fruit development. Support for these predictions would indicate that sensor cameras can effectively detect pollinator visits associated with successful pollination.

2 | MATERIALS AND METHODS

A survey was conducted from 2019 to 2025 in the Kakuma Satoyama Zone (36°32′N, 136°42′E) of the Kanazawa University Kakuma Campus in Kanazawa City, Ishikawa Prefecture, central Japan. This site is covered by secondary deciduous broadleaf forest approximately 75 ha in area, with elevations of 50–160 m. The forest is dominated by *Quercus variabilis* and *Q. serrata*, with *Sasa palmata* being common on the forest floor (Kitabayashi et al., 2022). Based on 30-year climate records (1993–2023), the average temperature and precipitation in Kanazawa during May are 17.9°C and 145 mm, respectively. These meteorological data were obtained from the Kanazawa Local Meteorological Office, situated approximately 7.7 km from the study site (Japan Meteorological Agency, 2025).

This study focused on *Cremastra appendiculata* var. *variabilis*, which grows naturally along approximately 1 km of road within the study area. This species is distributed from southern Sakhalin and the Korean Peninsula to China and the Himalayas. In Japan, it is a perennial herb that grows on the forest floor in mountainous areas from Hokkaido to Kyushu, producing 10–20 flowers with plentiful nectar per inflorescence from May to June (Figure 1a) (Sugiura, 1996). *Cremastra appendiculata* var. *variabilis* produces only one inflorescence per individual. In 2015, flowering was observed at the study site between May 7 and June 11 (Watanabe et al., 2017). In two previous studies examining pollinators of this species, the only insect observed to bear attached pollinia was a *Bombus diversus* queen (Kubo & Ono, 2017; Sugiura, 1996). Although *C. appendiculata* var. *variabilis* is self-compatible, automatic self-pollination is lacking, rendering a pollinator essential (Chung & Chung, 2003).

2.1 | Sensor camera deployment, pollinator detection, and ambient temperature validation

Pollinators of *Cremastra appendiculata* var. *variabilis* were recorded by sensor cameras from 2019 to 2022. Camera deployment began prior to anthesis. Elongated inflorescences of *C. appendiculata* var. *variabilis* were labeled with number tape and pegs. A Ltl-Acorn 6210 MC sensor camera (Shenzhen Ltl Acorn Electronics, Ltd., Zhuhai, China) was then installed on a tripod near each marked individual. All flowers per inflorescence were



FIGURE 1 *Cremastra appendiculata* var. *variabilis* inflorescence. (a) Flowering inflorescence. (b) After flowering, pollinated flowers exhibit mature and swollen ovaries.

included in the camera's frame; nevertheless, elongation of the inflorescences occasionally caused them to move out of frame for several days. The cameras were configured to record 60-s videos at 30 frames/s, with no interval between recordings. The sensor sensitivity was set to the highest possible setting. Although the recommended focal distance for this model is 120–250 cm, we modified the camera lens, following Kodaka et al. (2022) and Seki (2023), by removing the outer camera casing and rotating the screw-in lens located beneath the infrared filter counterclockwise by approximately 10°, which changed the minimum focusing distance to 30–50 cm. At a minimum focal distance of 50 cm, the camera's field of view was approximately 32 × 19 cm. Eight batteries (Eneloop Pro; Panasonic, Newark, NJ, USA) powered the camera, and a 32-GB secure digital (SD) card recorded all videos.

During initial sensor camera installation, we visited the study site every 3–5 days to check the cameras. During these checks, the number of flowers on each inflorescence and the number of pollinia removed from flowers were visually counted. Sensor cameras were retrieved once all inflorescences had ceased flowering. After the survey, fruits were visually counted on all inflorescences. Mature and swollen ovaries were considered to be fruits (Figure 1b).

The detection performance of sensor cameras is influenced by the ambient temperature surrounding the device. Although the main ecological survey was conducted from 2019 to 2023, ambient temperature during the flowering period of *Cremastra appendiculata* var. *variabilis* was monitored in 2025 to evaluate sensor performance under typical field conditions. From 1 May to 20 June 2025, temperature loggers (TR-51I; T&D, Tokyo, Japan) were installed at a height of approximately 70 cm above ground level across eight sampling points inhabited by *C. appendiculata* var. *variabilis*, recording ambient temperature at hourly intervals. This height was slightly above the inflorescences of *C. appendiculata* var. *variabilis* and closely matched the typical installation height of the sensor cameras used in the survey.

To estimate ambient temperatures during 2019–2022, we applied a linear regression model using R 4.5.1 (R Core Team, 2025), based on 2025 logger data and meteorological records. In this model, hourly temperature data from the Kanazawa Meteorological Office served as the explanatory variable, while the mean temperature across the eight sampling points was used as the response variable. The resulting regression equation was then applied to historical hourly temperature records from the Kanazawa Meteorological Office (2019–2022) to estimate ambient temperatures at the study site during the ecological survey period. Using these estimated hourly values, we calculated the range (minimum and maximum) and mean ambient temperatures for the specific periods when the sensor cameras were active. This approach allowed us to approximate site-level thermal conditions during past surveys with high temporal resolution. This approximation was supported by a strong correlation between logger data and meteorological records during the 2025 monitoring period ($R^2 = 0.89$; Figure S1), suggesting that the regression model reliably captured local temperature variation. Notably, ambient temperatures recorded by the Kanazawa Meteorological Office during the 2025 monitoring period did not differ substantially from the 30-year average (1991–2020), indicating that the conditions used for model validation were representative of typical regional climate.

2.2 | Performance comparisons between sensor and scheduled cameras in detecting *Bombus diversus*

In 2023, eight trials were conducted using sensor and scheduled cameras to simultaneously record insects visiting the same inflorescences of *C. appendiculata* var. *variabilis*. In total, 10 inflorescences were targeted, with one Ltl-Acorn 6210 sensor camera installed per inflorescence. The Ltl-Acorn MINI30 was used as the scheduled camera. One scheduled camera was installed per inflorescence during trials 1–4, and one scheduled camera was placed to cover two adjacent blooming inflorescences during trials 5–8 (Figure 2). Trials 7 and 8 were conducted on separate days but targeted the same inflorescences.

Sensor camera settings followed the configuration described above. The Ltl-Acorn MINI30 used as a scheduled camera was set to video mode, with a recording duration of 60 s. The time-lapse function was enabled, and the recording interval was set to 5 min, resulting in one 60-s video being recorded every 5 min. The camera was mounted on a tripod 60 cm from the inflorescence. The field of view was 150 × 65 cm. Four Panasonic Eneloop Pro batteries were used as the power source, and a 32-GB microSD card was used as the recording medium.

Sensor cameras were deployed prior to the onset of flowering and remained in place until all flowers had wilted. The scheduled cameras were placed during the flowering period and continued recording until the microSD cards were full. In each trial, the total numbers of videos and the numbers of videos capturing bumblebee queens were compared between the two cameras.

2.3 | Video analysis

Videos that captured any animal's presence were considered valid. If an insect was recorded, it was identified to the most detailed taxonomic level possible. If an insect visited a flower, we checked whether *C. appendiculata* var. *variabilis* pollinia were attached to that insect at the start of the video. Generally, a series of flower visitations recorded in a single video was considered a single visit. If such behavior was recorded at the same inflorescence in several consecutive videos taken by the sensor camera over more than 60 s, and the time between videos was less than 2 min, then it was assumed to reflect one visit by the same individual. The number of flower visits by each species was recorded. The sensor camera's animal-detection rates are influenced by the temperature difference between the background and the moving object; therefore, temperatures printed on videos capturing flower-visiting insects were recorded and later analyzed to assess detection performance under various thermal conditions.

Of the videos recorded by the scheduled camera, those shorter than 60 s because of a voltage drop and those for which the times between the preceding and following videos exceeded 5 min were excluded from analysis. In each trial, the total number of videos and the number of videos capturing bumblebee queens were compared between the two cameras to evaluate their relative effectiveness in detecting pollinator visits.

3 | RESULTS

3.1 | Sensor camera detection of *Bombus diversus* queen visits and other insects

From 2019 to 2022, 151 sensor cameras were deployed at 151 inflorescences of *Cremastra appendiculata* var. *variabilis* (range 5–31 flowers per inflorescence). However, one camera was knocked over by an animal and another malfunctioned in 2021, resulting in no data being collected from these two units. In total, the deployment yielded 2707 camera days and 35 610 recorded videos. Of these, 2143 videos were deemed valid (Table 1). In total, 1171 videos documented insects contacting flowers, accounting for 54.6% of all valid recordings (Table 2). Among the valid videos, 885 captured *Bombus diversus* queens. Of the 885 videos, 878 showed queens visiting flowers (Video S1), while 7 showed hovering near inflorescences without landing on flowers (Table 1). Among them, 772 videos documented *B. diversus* queens carrying pollinia (Table 2). In contrast to previous studies, our recordings included several other insects such as *B. ardens* (Video S2), halictid and andrenid bees, dipteran insects, and lepidopteran insects (Table 2). Solitary bees and Syrphinae hoverflies frequently contacted flowers but did not carry pollinia. Likewise, the nocturnal visitors, including one Plusiinae species and two Sphingidae species (Video S3), were recorded inserting their proboscises

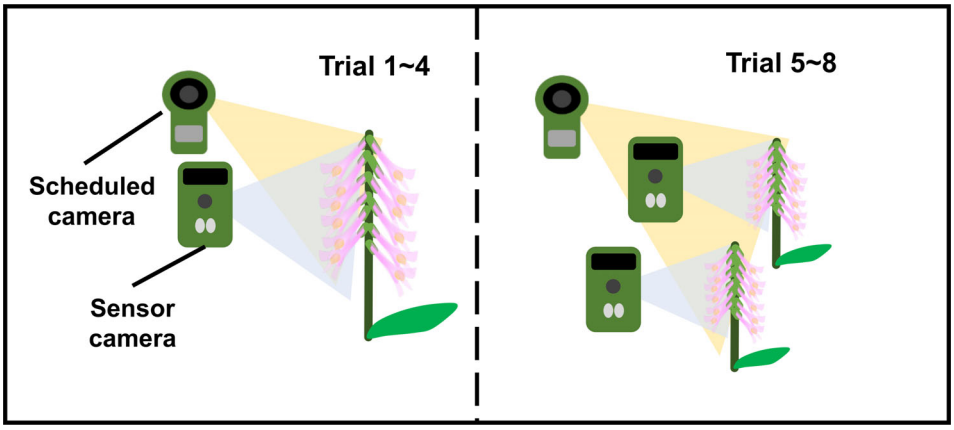


FIGURE 2 Experimental setup for comparing sensor and scheduled cameras. Each camera was positioned to monitor inflorescences of *Cremastra appendiculata* var. *variabilis* under identical conditions.

TABLE 1 Numbers of inflorescences evaluated, and numbers of videos acquired per year from 2019 to 2022.

Year	No. of inflorescences	Camera days	Total no. of videos	No. of valid videos	No. of videos showing *Bombus diversus* queens	No. of visiting videos
2019	19	349	4764	183	0	0
2020	26	563	6137	242	17	16
2021	50	911	9240	650	447	442
2022	54	884	15 469	1068	421	420
Total	149	2707	35 610	2143	885	878

into flowers, yet lacked pollinia. In 2020, 27 videos captured 20 visits by *B. ardens* queens; however, none carried pollinia. Overall, only *B. diversus* queens were observed with pollinia attached.

3.2 | Relationship between reproductive success and bumblebee visitation

No *Bombus diversus* queens were recorded in 2019 (Table 3). From 2020 to 2022, however, queens were consistently observed visiting flowers (Figure 3; Table 3). Across the 4-year period, 149 inflorescences were monitored. Pollinia removal was observed in 105 inflorescences, 96% of which (101) had recorded visits by *B. diversus* queens (Table 4), while four inflorescences lacked recorded queen visits (Table 4). One case was attributed to predation by *Lemyra imparilis* larvae, while the causes in the remaining three cases were unknown. All inflorescences that produced fruit during this period had been visited by queens carrying pollinia. In contrast, 40 inflorescences showed neither pollinia removal nor fruit production, and no queen visits were recorded at these inflorescences. Additionally, among the inflorescences visited by *B. diversus* queens carrying pollinia, 10 did not produce fruit (Table 3). Inflorescences visited exclusively by *B. ardens* showed neither pollinia removal nor fruit development.

TABLE 2 Insects visiting *Cremastra appendiculata* var. *variabilis* and numbers of videos recorded by sensor cameras between 2019 and 2022.

Visiting insects	Number of visiting videos	Pollinia videos
Bombus diversus (Q)	878	772
Bombus ardens (Q)	27	0
Bombus ardens (W)	5	0
Bombus ardens (M)	1	0
Halictidae sp.	18	0
Andrenidae sp.	1	0
Diptera spp.	200	0
Bacchini sp.	24	0
Syrphinae sp.	6	0
Plusiinae sp.	2	0
Sphingidae sp.1	1	0
Sphingidae sp.2	1	0
Total	1164	–

Note: Only insects that exhibited flower-touching behavior in the videos are listed. M, male bees; Q, queen bees; W worker bees. Pollinia videos present the number of videos that shot individual carrying pollinia.

3.3 | Estimated air temperature during camera recording

Bumblebee queens were recorded at all daytime hours, including during the warmer periods of the day (Figure 4). The mean air temperature at the eight sampling points within the study site, measured using temperature loggers, was estimated by regression model to be approximately 1.5°C lower than that recorded at the Kanazawa Meteorological Office (Figure S1). During the survey periods from 2019 to 2022, the estimated ambient temperatures at the sampling points ranged from 5.4°C to 28.2°C, with a mean of 17.8°C. Notably, the highest temperature recorded by the sensor camera during *Bombus diversus* queen visits was 28°C (Figure S2), which, although measured at a different temporal resolution, was nearly equivalent to the estimated peak.

3.4 | Performance comparison between sensor and scheduled cameras in detecting *Bombus diversus*

Over the eight trial periods, the operating time of the scheduled camera averaged 675 min (range: 445–985 min), recording an average of 141 videos (range 92–210) (Table 5). Camera batteries were replaced in trials 2 and

TABLE 3 Numbers of inflorescences visited by *Bombus diversus* queens and numbers of fruiting inflorescences per year from 2019 to 2022.

Year	No. of monitored inflorescences	No. of inflorescences visited by *B. diversus* queens	No. of fruiting inflorescences	No. of fruits
2019	19	0	0	0
2020	26	5	3	5
2021	50	48	41	225
2022	54	52	50	285
Total	149	105	94	515

Note: Note that the dataset of inflorescences visited by *Bombus diversus* queens includes one sample from 2020 in which the visiting queen was not carrying pollinia. All other inflorescences were visited at least once by a queen carrying pollinia.



FIGURE 3 *Bombus diversus* queen visiting *Cremastra appendiculata* var. *variabilis*, recorded by an Ltl-Acorn 6210 MC camera. White arrows indicate pollinia attached to the forelegs.

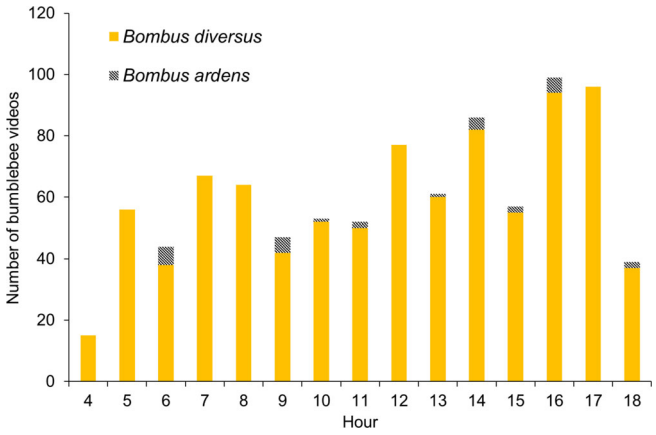


FIGURE 4 Temporal distribution of 912 bumblebee queen videos recorded between 2020 and 2022. Video counts are classified by time of day: *Bombus diversus* ($n = 885$) and *B. ardens* ($n = 27$). Bumblebee visitation was not detected during 1900–0400.

4, and SD cards were replaced once in seven trials and twice in one trial (Table S1).

Across the eight trials, the sensor camera recorded bumblebee queens of two species (*Bombus diversus* and *B. ardens*) in 7 of 50 videos, while the scheduled camera recorded them in 3 of 1128 videos. In two instances, bumblebees were recorded only by the scheduled camera, while in four instances they were recorded only by the sensor camera (Table 5). No pollinia removal from inflorescences was observed in which bumblebee visits were not recorded by either camera.

4 | DISCUSSION

This study used commercially available infrared sensor cameras to record 885 videos of *Bombus diversus* queens, the pollinators of *Cremastra appendiculata* var. *variabilis*. To the best of our knowledge, this is the first documentation of bumblebee queen visits to a wild plant using commercial sensor cameras. Observations were conducted over 4 years, covering 2707 camera days, and spanned the full flowering period of *C. appendiculata* var. *variabilis* each year. Throughout the study, only *B. diversus* queens were observed with attached pollinia, and notably, neither pollinia removal nor fruit production was noted in inflorescences where no visit was recorded. Although Sugiura (1996) and Kubo and Ono (2017) previously identified *B. diversus* queens as pollinators of *C. appendiculata* var. *variabilis*, our multi-year, flowering-period-wide observations, including nighttime monitoring, confirm that other insect species also visit the flowers but do not carry pollinia.

The strong correspondence between queen visitation and pollinia removal supports the conclusion that *B. diversus* queens were the primary agents of pollination and fruit set in this system. While quantitative validation against continuous recording is necessary to fully test the sensor camera's detection completeness, our results indicate that the method is highly effective for capturing visits that result in reproductive success. Although sensor cameras may have been triggered by various movements, our focus was on identifying legitimate pollinators contributing to reproductive success. It is possible that the sensor camera missed some approaches, particularly those without floral access or of very short duration. However, in this study, sensor cameras successfully recorded the specific visits that contributed to pollination success (i.e., pollinia removal and fruit set). This suggests that visits critical for plant reproduction were reliably detected, whereas visits that do not contribute to pollination success—such as those without floral access or with very short time visitation—may be missed.

TABLE 4 Reproductive success of individual inflorescences of *Cremastra appendiculata* var. *variabilis* and the presence or absence of visits by *Bombus diversus* queens from 2019 to 2022.

	Male success		Female success	
***Bombus diversus* queens**	**Pollinia removal**	**No pollinia removal**	**Fruiting**	**No fruiting**
Visit	101	4	94	11
No visit	4	40	0	44

Note: Numbers indicate the number of corresponding inflorescences.

TABLE 5 Numbers of inflorescences, trial times, and videos recorded by the sensor cameras and scheduled cameras.

			Total videos		Bumblebee videos	
Trial	**Inflorescence ID**	**Time (min)**	**Sensor**	**Scheduled**	**Sensor**	**Scheduled**
1	539	985	8	198	0	0
2	627	915	16	210	1 (1)	2 (2)
3	610	540	6	111	0	0
4	580	506	0	106	0	0
5	519, 602	924	10	188	3 (2)	0
6	514, 515	554	0	113	0	0
7	605, 606	534	1	110	0	0
8	605, 606	445	9	92	3 (1)	1 (1)

Note: Time (min) refers to the operating time of the scheduled camera. Numbers of bumblebee videos are combined totals of videos in which *Bombus diversus* (Trial 2 and 5) and *B. ardens* (Trial 8) were recorded, and numbers in parentheses are the numbers of independent visits.

Compared to the scheduled camera, the sensor camera recorded far fewer videos but captured more bumblebee visits (Table 5). This reduction in invalid recordings significantly decreased the time required for video review. In Trial 2 only, the scheduled camera recorded a *B. diversus* visit that was missed by the sensor camera, probably because it did not capture the entire inflorescence, and the bumblebee acted outside the sensor's detection zone. For long-term deployments, it is advisable to check regularly whether a target flower remains within the camera field of view and whether any obstacles obscure the view.

Cameras with infrared sensors capture images by detecting temperature differences between the background and a moving object. If a passive infrared sensor is to detect an animal, that animal must be 2.7°C warmer than its surroundings and it must move across the field of view (Meek et al., 2012). In a previous study using an Ltl-Acorn 5210, an older model of the Ltl-Acorn 6210 employed in this study, the detection rate decreased when the temperature difference between the background and the surface of the moving object fell below 6°C (Yamada & Ando, 2015). These camera characteristics imply that missed detections are more likely when an increase in temperature reduces the temperature difference between the background and the body surface of the animal.

In this study, *B. diversus* queens were recorded at various times throughout the day, including during warmer periods (Figure 4). This consistent detection is likely due to their high thoracic body temperature during flight. For example, queens of *Bombus vosnesenskii* maintain thoracic temperatures of 35–45°C while flying (Heinrich, 1975), which creates a strong thermal contrast with the background—an essential condition for infrared sensor detection. During the flowering period of *C. appendiculata* var. *variabilis* (May–June), ground surface temperatures in deciduous broadleaf forests remain relatively low due to canopy shading during leaf expansion. In a *Quercus serrata* forest, continuous 24-hour measurements showed that ground temperatures rarely exceeded 17.1°C between mid-May and mid-June (Hashizume et al., 1987). Similarly, in our study, ambient temperatures around inflorescences were estimated to be approximately 1.5°C lower than those recorded at the Kanazawa Local Meteorological Office. Under such forest floor conditions, only insects that maintain a consistently high body temperature relative to their surroundings—such as bumblebee queens—are likely to be detected. This suggests that although the cameras were originally designed to detect mammals and birds, they were

well-suited for capturing large, warm-bodied insects like *B. diversus* in shaded forest environments.

Many previous studies on pollinators have employed scheduled cameras to capture still images of flower-visiting insects (e.g., Edwards et al., 2015). In contrast, we videorecorded flower-visiting insects. It has been suggested that pollinator behavior on flowers can influence pollination efficacy, because both the pollen attachment site and the amount of pollen attached can vary (Russell et al., 2021). *Xylocopa appendiculata* visiting *C. appendiculata* var. *variabilis* destroys floral structures and robs nectar (Sugiura, 1996). A detailed analysis of our videos implied that *B. ardens* queens foraged on *C. appendiculata* var. *variabilis* flowers in a manner distinct from that of *B. diversus* queens, and that flower-visiting behavior was not associated with pollinia attachment (Shimada et al. unpublished data). Recording insect behavior on flowers is crucial when seeking to understand whether a flower-visiting insect contributes to plant reproduction. The maximum video recording time of the scheduled camera used was 11.25 h. Such recording consumes power and storage space more quickly than does the capture of still images, which requires shorter shooting times. A sensor camera allows flower-visiting insects to be recorded for longer periods and has lower power and storage requirements.

Social bumblebee queens use forests for overwintering, nesting, and foraging (Mola et al., 2021). Aside from *Cremastra appendiculata* var. *variabilis*, other herbaceous species visited by bumblebee queens in Japanese forests include *Monotropastrum humile* (Suetsugu et al., 2023), *Epimedium* spp. (Suzuki, 1984), and *Polygonatum odoratum* var. *pluriflorum* (Ohara et al., 2007), all of which are thought to significantly influence bumblebee reproductive success. Carvell et al. (2017) found that, for three bumblebee species, the coverage of spring plants foraged by queens around the colony positively influenced the survival rate of the next-generation queens in the following year. However, most prior studies on bumblebee foraging have focused on worker bees operating in open environments (Goulson, 2010). Quantitative observations of queen behaviors in forests are few in number. Our method measures the number of bumblebee queen visits to forest herbaceous plants, enhancing our understanding of queens' behavior in such environments.

Previous studies using commercially available sensor cameras have demonstrated their utility in capturing large or endothermic flower-visiting animals, such as large carpenter bees, wasps, and hawkmoths (Johnson, 2024a; Shaw-Bonner et al., 2023; Johnson & Balducci 2024). Our study extends this application to forest-floor herbs, confirming that sensor cameras are also well-suited for monitoring bumblebee queens—large, warm-bodied insects—even in shaded environments. This capability is particularly valuable for extended monitoring periods, including nighttime, which is often challenging with traditional observation methods. While we recorded some nocturnal moths, validating the camera's efficiency for these insects remains difficult without reliable proxies like pollinia removal. Nevertheless, for target species that maintain high body temperatures or have large body sizes, sensor cameras provide an effective, scalable, and non-invasive monitoring tool.

Conversely, sensor cameras have distinct limitations regarding smaller or heterothermic insects. In this study, visits by small solitary bees and Syrphinae flies were recorded; however, these were likely triggered incidentally by external factors such as wind-induced vegetation movement or sunflecks rather than the insects themselves. Consequently, sensor cameras are likely to underestimate the diversity and frequency of visits by smaller taxa. This suggests that while sensor cameras are excellent for focused studies on specific "effective" pollinators like bumblebee queens, they may not be appropriate for community-level network studies that require comprehensive records of all diverse flower-visiting animals. Future research should carefully select camera models and recording methods based on the target pollinators' size and thermal characteristics.

In summary, our findings demonstrate that commercially available sensor cameras can effectively detect bumblebee queen visits to herbaceous plants in forests, particularly when their body temperature contrasts with the background temperature. While limitations exist in detecting small heterothermic insects, sensor cameras offer a valuable tool for long-term, low-maintenance monitoring of effective pollinators in forest ecosystems. These findings underscore the potential of sensor cameras as a scalable, noninvasive tool for detecting effective pollinators in forest ecosystems, especially under conditions in which traditional observations are limited.

AUTHOR CONTRIBUTIONS

Kaito Suenaga, Masahiko Shimada, and Shumpei Kitamura conducted the conception and the design of the work. Kaito Suenaga, Masahiko Shimada, and Shumpei Kitamura conducted data collection. Kaito Suenaga and Masahiko Shimada conducted statistical analysis. Masahiko Shimada and Shumpei Kitamura wrote the first draft of the manuscript. All authors approved the final version of the manuscript to be published.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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REFERENCES

Ackerman, J. D., Phillips, R. D., Tremblay, R. L., Karremans, A., Reiter, N., Peter, C. I., Bogarín, D., Pérez-Escobar, O. A., & Liu, H. (2023). Beyond the various contrivances by which orchids are pollinated: Global patterns in orchid pollination biology. *Botanical Journal of the Linnean Society*, *202*, 295–324. https://doi.org/10.1093/botlinnean/boac082

Albrecht, M., Schmid, B., Hautier, Y., & Müller, C. B. (2012). Diverse pollinator communities enhance plant reproductive success. *Proceedings of the Royal Society B: Biological Sciences*, *279*, 4845–4852. https://doi.org/10.1098/rspb.2012.1621

Alison, J., Alexander, M. J., Zeugin, D. N., Dupont, L. Y., Iseli, E., Mann, R. M. H., & Hoye, T. T. (2022). Moths complement bumblebee pollination of red clover: A case for day-and-night insect surveillance. *Biology Letters*, *18*, 20220187. https://doi.org/10.1098/rsbl.2022.0187

Apps, P. J., & McNutt, J. W. (2018). How camera traps work and how to work them. *African Journal of Ecology*, *56*, 702–709. https://doi.org/10.1111/aje.12563

Burton, A. C., Neilson, E., Moreira, D., Ladle, A., Steenweg, R., Fisher, J. T., Bayne, E., & Boutin, S. (2015). Wildlife camera trapping: A review and recommendations for linking surveys to ecological processes. *Journal of Applied Ecology*, *52*, 675–685. https://doi.org/10.1111/1365-2664.12432

Carvell, C., Bourke, A., Dreier, S., Freeman, S. N., Hulmes, S., Jordan, W. C., Redhead, J. W., Sumner, S., Wang, J., & Heard, M. S. (2017). Bumblebee family lineage survival is enhanced in high-quality landscapes. *Nature*, *543*, 547–549. https://doi.org/10.1038/nature21709

Chung, M. Y., & Chung, M. G. (2003). The breeding systems of *Cremastra appendiculata* and *cymbidium goeringii*: High levels of annual fruit failure in two self-compatible orchids. *Annales Botanici Fennici*, *40*, 81–85.

Droissart, V., Azandi, L., Onguene, E. R., Savignac, M., Smith, T. B., & Deblauwe, V. (2021). PICT: A low-cost, modular, open-source camera trap system to study plant–insect interactions. *Methods in Ecology and Evolution*, *12*, 1389–1396. https://doi.org/10.1111/2041-210X.13618

Edwards, J., Smith, G. P., & McEntee, M. H. F. (2015). Long-term time-lapse video provides near complete records of floral visitation. *Journal of Pollination Ecology*, *16*, 91–100. https://doi.org/10.26786/1920-7603(2015)16

Fründ, J., Dormann, F. C., Holzschuh, A., & Tschamtke, T. (2013). Bee diversity effects on pollination depend on functional complementarity and niche shifts. *Ecology*, *94*, 2042–2054. https://doi.org/10.1890/12-1620.1

Goulson, D. (2010). *Bumblebees: Behaviour, ecology, and conservation* (2nd ed.). Oxford University Press.

Hashizume, H., Sakamoto, D., & Wada, H. (1987). Observation of microclimate in deciduous broad-leaved forests of the Hiruzen Experimental Forest of Tottori University. *Hardwood Research*, *4*, 223–256. in Japanese.

Heinrich, B. (1975). Thermoregulation in bumblebees: II. Energetics of warm-up and free flight. *Journal of Comparative Physiology*, *96*, 155–166.

Hobbs, M. T., & Brehme, C. S. (2017). An improved camera trap for amphibians, reptiles, small mammals, and large invertebrates. *PLoS One*, *12*(10), e0185026. https://doi.org/10.1371/journal.pone.0185026

Høye, T. T., Montagna, M., Oteman, B., & Roy, D. B. (2025). Emerging technologies for pollinator monitoring. *Current Opinion in Insect Science*, *69*, 101367.

Japan Meteorological Agency. (2025). Meteorological data of the past. https://www.data.jma.go.jp/obd/stats/etrn/

Johnson, D. S. (2024a). Pollination of *Disa engleriana* (Orchidaceae): Floral modifications for deposition of pollinaria on the abdomen of large bees and wasps. *Flora*, *314*, 152491. https://doi.org/10.1016/j.flora.2024.152491

Johnson, D. S. (2024b). Butterfly pollination in *Platycoryne* (Orchidaceae): Evidence for a key pollinator shift in the large *Habenaria* clade. *Plant Systematics and Evolution*, *310*, 21. https://doi.org/10.1007/s00606-024-01895-1

Johnson, D. S. (2024c). Pollination of *Chamaepentas nobilis* (Rubiaceae) by long-proboscid hawkmoths in south-central Africa: Trait mismatching and floral scent chemistry. *Biotropica*, *56*, 161–169. https://doi.org/10.1111/btp.13293

Johnson, D. S., & Balducci, G. (2024). Settling moth pollination of a rare orchid in the *Habenaria* clade revealed with close-focusing camera traps. *Plant Biology*, *26*, 920–928. https://doi.org/10.1111/plb.13696

Kitabayashi, K., Kitamura, S., & Tuno, N. (2022). Fungal spore transport by omnivorous mycophagous slug in temperate forest. *Ecology and Evolution*, *12*, e8565. https://doi.org/10.1002/ece3.8565

Kodaka, N., Yasuda, M., & Shimada, T. (2022). Development of a camera-installed Nest box for small mammals and its application in reproductive schedule estimation for the Okinawa spiny rat. *Mammal Study*, *47*(2), 77–85. https://doi.org/10.3106/ms2021-0025

Krauss, S. L., Roberts, D. G., Phillips, R. D., & Edwards, C. (2018). Effectiveness of camera traps for quantifying daytime and nighttime visitation by vertebrate pollinators. *Ecology and Evolution*, *8*, 9304–9314. https://doi.org/10.1002/ece3.4438

Kubo, R., & Ono, M. (2017). Queens of *Bombus diversus tersatus* (Hymenoptera: Apidae) are innately attracted to floral scents emitted by *Cremastra appendiculata* (Orchidaceae). *Canadian Entomologist*, *149*, 372–376. https://doi.org/10.4039/tce.2017.2

Lahondere, C., Vinauger, C., Okubo, P., R., Wolff, H., G., Chan, K., J., Akbari, S., O., & Riffell, A., J. (2020). The olfactory basis of

orchid pollination by mosquitoes. *Proceedings of the National Academy of Sciences*, *117*, 708–716. https://doi.org/10.1073/pnas.1910589117

Meek, P., Ballard, G., & Fleming, P. (2012). *An introduction to camera trapping for wildlife surveys in Australia* (V1 ed.). Invasive Animals CRC.

Mola, J. M., Hemberger, J., Kochanski, J., Richardson, L. L., & Pearse, I. S. (2021). The importance of forests in bumble bee biology and conservation. *Bioscience*, *71*, 1234–1248. https://doi.org/10.1093/biosci/biab121

Naqvi, Q., Wolff, P. J., Molano-Flores, B., & Sperry, J. H. (2022). Camera traps are an effective tool for monitoring insect–plant interactions. *Ecology and Evolution*, *12*, e8962. https://doi.org/10.1002/ece3.8962

O'Connell, A., Nichol, J., & Karanth, K. (2011). *Camera traps in ecology: Methods and analyses*. Springer Science & Business Media. https://doi.org/10.1007/978-4-431-99495-4

Ohara, M., Tamura, M., Hirose, T., Hiei, K., & Kawano, S. (2007). 8: *Polygonatum odoratum* (Miller) Druce var. *pluriflorum* (Miq.) Ohwi (Convallariaceae). *Plant Species Biology*, *22*, 59–64. https://doi.org/10.1111/j.1442-1984.2007.00177.x

Ollerton, J. (2017). Pollinator diversity: Distribution, ecological function, and conservation. *Annual Review of Ecology, Evolution, and Systematics*, *48*, 353–376. https://doi.org/10.1146/annurev-ecolsys-110316022919

Ollerton, J., Winfree, R., & Tarrant, S. (2011). How many flowering plants are pollinated by animals? *Oikos*, *120*, 321–326. https://doi.org/10.1111/j.1600-0706.2010.18644.x

Pegoraro, L., Hidalgo, O., Leitch, I. J., Pellicer, J., & Barlow, S. E. (2020). Automated video monitoring of insect pollinators in the field. *Emerging Topics in Life Sciences*, *4*(1), 87–97. https://doi.org/10.1042/ETLS20190074

R Core Team. (2025). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Russell, A. L., Fetters, A. M., James, E. I., & Ashman, T.-L. (2021). Pollinator effectiveness is affected by intraindividual behavioral variation. *Oecologia*, *197*, 189–200. https://doi.org/10.1007/s00442-021-05016-4

Seki, S. (2023). Breeding biology of the varied tit in the subtropical broad-leaved forests of Okinawa-jima Island. *Bird Research*, *19*, A51–A61. in Japanese.

Shaw-Bonner, K., Theron, G., Adedoja, O., Bester, C., & Geerts, S. (2023). The importance of wild pollinators for indigenous crop pollination: The case of *cyclopia* (honeybush). *South African Journal of Botany*, *161*, 281–292. https://doi.org/10.1016/j.sajb.2023.08.015

Smith, J. A., Suraci, J. P., Hunter, J. S., Gaynor, K. M., Keller, C. B., Palmer, M. S., Atkins, J. L., Castañeda, I., Cherry, M. J., Garvey, P. M., Huebner, S. E., Morin, D. J., Teckentrup, L., Weterings, M. J. A., & Beaudrot, L. (2020). Zooming in on mechanistic predator–prey ecology: Integrating camera traps with experimental methods to reveal the drivers of ecological interactions. *Journal of Animal Ecology*, *89*, 1997–2012. https://doi.org/10.1111/1365-2656.13264

Steen, R. (2017). Diel activity, frequency and visit duration of pollinators in focal plants: In situ automatic camera monitoring and data processing. *Methods in Ecology and Evolution*, *8*, 203–213. https://doi.org/10.1111/2041-210X.12654

Suetsugu, K., Hirota, S. K., Hsu, T.-C., Kurogi, S., Imamura, A., & Suyama, Y. (2023). *Monotropastrum kirishimense* (Ericaceae), a new mycoheterotrophic plant from Japan based on multifaceted evidence. *Journal of Plant Research*, *136*, 3–18. https://doi.org/10.1007/s10265-022-01422-8

Suetsugu, K., & Tanaka, K. (2013). Pollination of *Sedirea japonica* (Orchidaceae) by *Bombus diversusdiversus* (Hymenoptera: Apidae). *European Journal of Entomology*, *110*, 545–548.

Sugiura, N. (1996). Pollination biology of *Cremastra appendiculata* var. *variabilis* (Orchidaceae). *Plant Species Biology*, *11*, 185–187.

Suzuki, K. (1984). Pollination system and its significance on isolation and hybridization in Japanese *epimedium* (Berberidaceae). *The Botanical Magazine, Tokyo*, *97*, 381–396.

Thomann, M., Imbert, E., Devaux, C., & Cheptou, P.-O. (2013). Flowering plants under global pollinator decline. *Trends in Plant Science*, *18*, 353–359. https://doi.org/10.1016/j.tplants.2013.04.002

van Klink, R., Sheard, J. K., Hoye, T. T., Roslin, T., Do Nascimento, L. A., & Bauer, S. (2024). Towards a toolkit for global insect biodiversity monitoring. *Philosophical Transactions of the Royal Society B*, *379*, 20230101. https://doi.org/10.1098/rstb.2023.0101

van der Niet, T., Cozien, J. R., Castaneda-Zarate, M., & Johnson, D. S. (2022). Long-term camera trapping needed to identify sunbird species that pollinate the endangered South African orchid *Satyrium rhodanthum*. *African Journal of Ecology*, *60*, 1278–1282. https://doi.org/10.1111/aje.13058

Watanabe, K., Shirai, N., Ikejima, M., Hoshi, K., Kinoshita, E., & Kitamura, S. (2017). Flowering phenology of angiosperms in a secondary forest of the Kakuma, Kanazawa, Japan. *Bulletin of Ishikawa Museum of Natural History*, *7*, 37–50. in Japanese.

Yamada, H., & Ando, M. (2015). Influence of the background and body surface temperatures on detection rates of Pyroelectric-sensor-type Trail cameras. *Journal of Agriculture Science, Tokyo University of Agriculture*, *60*, 57–62. in Japanese.

Zhang, S. M., Peng, W. S., & Wang, W. (2010). Macro research on growth and development of *Cremastra appendiculata* (D.Don.) Makino (Orchidaceae). *Journal of Medical Plant Research*, *4*(18), 1837–1842.

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