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Behaviour of European Spruce Bark Beetle—*Ips typographus* (L.) on Poisoned Traps

Kula Emanuel[1] | Hrdlička Petr[2]

[1]Department of Forest Protection and Game Management, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic | [2]Department of Chemistry and Biochemistry, Faculty of AgriSciences, Mendel University in Brno, Brno, Czech Republic

Correspondence: Hrdlička Petr (hrdlicka@mendelu.cz)

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ABSTRACT

Deployment of poisoned trap trees/logs is an efficient suppressive method to fight *Ips typographus* (L., 1758) (Coleoptera: Curculionidae: Scolytinae), a calamity pest of spruce stands in the European area during the gradation period. Logs from *Picea abies* (L.) H. Karst., 1881 (Pinales: Pinaceae) laid as traps were baited with IT Ecolure pheromone and were treated with Forester insecticide containing cypermethrin as the active substance. Catching frames were placed under the pheromone trap to gather dead imagines. Behaviour of imagines was observed directly in the field and recorded by camera; video records were evaluated in the laboratory. Higher mean air temperature affected favourably the flight activity of *Ips typographus* and increased the frequency of arrival on and departure from the surface of poisoned trap trees; the imagines stayed on the trap trees for a shorter time. The numbers of dead imagines under the trap trees did not depend on the temperature. The increasing number of live imagines on poisoned trap trees/logs correlated with the increasing proportion of caught dead imagines, decreasing length of live imagines staying on the trap tree, and increasing frequency of arrival to and departure from the trap tree. The presence of pheromone lure and insecticide treatment induced rectilinear and uninterrupted flight towards and away from the pheromone lure. No attempt was observed to gnaw an entrance hole. Mortality on the poisoned trap tree ranged from 18% to 21%; 40%–60% of poisoned imagines died later due to the contamination.

1 | Introduction

In the period of gradation, *Ips typographus* (L.) disrupts the stability of spruce stands throughout its distribution area (Stadelmann et al. 2013). Spruce stands can be protected by intensive removal of infested trees (Hlásny and Turčáni 2013; Stadelmann et al. 2013; Økland et al. 2016), catching bark beetles into various kinds of pheromone traps (Wall and Perry 1987; Jakuš and Blaženec 2002; Grégoire and Evans 2004; Galko et al. 2016) and poisoned trap trees (Kučera 1951; Martinek 1952; Grégoire and Evans 2004; Juha and Turčáni 2008). The advantage of poisoned trap trees is unlimited capacity and no need for control and sanitation (Lubojacký and Holuša 2011, 2014). Numerous studies have documented that insecticide-treated methods for trapping bark beetles have a significant negative effect on non-target invertebrates across various taxa and feeding groups (Bakke 1985; Valkama et al. 1997; Martikainen 2001; Duduman and Olenici 2015).

Despite the fact that the toxicity of pyrethroids is low (Raty et al. 1995) with the degradation time (DT_{50}) up to 60 days (Aznar-Alemany and Eljarrat 2020; Rivera-Dávila et al. 2022), a wide range of non-target organisms die after contact with the treated surface. Among the most endangered natural enemies of *I. typographus* are the species of the genus *Thanasimus*. Poisoned tripods cause mortality of *Thanasimus* spp. up to 11 times higher than Theysohn pheromone traps (Lubojacký and Holuša 2011). The design of the poisoned defence measure affects the arrival and mortality of *Thanasimus*, which was significantly lower on lying poisoned traps compared to tripods with Storanet nets (Kula et al. 2022). Similar differences in the number of non-target invertebrates affected are reported by (Špoula et al. 2025), when the negative impact on lying poisoned traps and Theysohn traps was balanced, but on standing poisoned logs, it was 5 times higher and on poisoned tripods 4.5 times higher. Of the 9663 pcs non-target invertebrates caught when baited with IT Ecolure pheromone, 17.4% were in the pheromone trap, 10.3% on a lying 4 m long poisoned trap and 72.3% on a poisoned tripod (Kula, Hrdlička unpublished data). Due to the negative influence on natural enemies, the treatment should be carried out only when the economic threshold of harmfulness is exceeded and the forest stability is put into threat (Skrzecz et al. 2015).

Spring swarming of *I. typographus* starts at a mean air temperature of 16.5°C during the day, its intensity increasing when the optimum of daily temperature reaches 22°C–26°C (Wermelinger 2004). It depends on solar radiation; imagines activity increases even after a short exposure to the sun (Lobinger and Skatulla 1996). The flight activity occurs between 9 and 21 h; during the spring period, it is intensive in the afternoon, and in summer in the midday sunlight (Zuber and Benz 1992). It culminates at an optimal temperature of 22°C–26°C (Funke and Petershagen 1994; Wermelinger 2004; Baier et al. 2007); 30°C is the upper limit (Lobinger 1994).

In natural conditions, searching and populating the tree, including regulation of density, is influenced by the pheromone communication of *I. typographus* (Bakke et al. 1977; Bakke 1981; Birgersson et al. 1984).

Poisoned trap trees have been set for sanitation of timber infested by bark beetles since the 1950s (Kučera 1951; Martinek 1952). Two types of pheromone-baited poisoned traps are used to monitor the occurrence of *I. typographus* and to protect spruce forest stands: lying poisoned stems or logs 2–4 m long or standing 1–2 m long logs arranged in the form of tripods (Grégoire et al. 1997; Grégoire and Evans 2004; Šotola et al. 2021; Kula et al. 2022; Šotola and Kula 2022).

According to other sources, fresh stem baited with pheromone lure increases attractiveness to maximum (Rudinsky et al. 1971; Švihra 1972; Bakke et al. 1977; Austarå et al. 1986; Johann 1986a, 1986b). Spruce volatiles, particularly in large amounts, seem to improve the attraction to the pheromone bait (Jakuš and Blaženec 2003; Erbilgin et al. 2007).

Experimental plan of reported research is based on a hypothesis of changes in the behaviour of imagines. Under optimum temperature conditions and at high population density of *I. typographus*, high amounts of imagines concentrate on the trap trees during the swarming culmination. Behaviour described during the infestation of trees in natural conditions could change due to increased pheromone concentration in the immediate surroundings of the pheromone lure (Birgersson et al. 1984; Schlyter and Löfqvist 1986). Disrupted communication around the pheromone lure and increased density of imagines on the stem treated with insecticide may manifest: (i) in males looking for a suitable place to create an entrance hole (length of motion and frequency of departures are affected); (ii) females attracted by pheromone lure cannot find created nuptial chambers. The change of behaviour could influence the character of movement along the trunk, length of stay and frequency of departures from the trunk. Efficiency of poisoned trap tree can be thus increased or decreased due to the behaviour change of *I. typographus*.

The study is based on whole-day catching of *I. typographus* imagines on the poisoned trap tree treated with Forester insecticide, baited with IT Ecolure pheromone and whole-day video record of their behaviour on the surface of the poisoned trap tree in the pheromone position. The aims were: (i) to determine the occurrence of *I. typographus* imagines on the trap tree as a function of temperature; (ii) to describe the behaviour of *I. typographus* imagines in terms of (a) the frequency of their arrivals to and departures from the trap tree, (b) movement and length of their stay on the surface as a function of the density of occurring individuals and air temperature. Research results will specify requirements for the preparation and application of poisoned trap trees.

2 | Materials and Methods

The project is focused on the optimisation of bark beetle capture methodology, including the definition of its behaviour on baited poisoned lying trap trees (further on trap tree/s) and baited poisoned lying trap logs (further on trap log/s). Both types of traps were baited with pheromone and treated with insecticide over the whole stem profile. Pheromone IT Ecolure classic—lure for *I. typographus* containing (S)-*cis*-verbenol (3%), alcohols and solvents (85.2%), and synergic components (11.8%) was packed in a classic clipping bag (Nakládal and Sova 2010; Ridex 2023). Insecticide Forester—commercial product intended for killing *I. typographus* and other bark beetles—contained 100 $g \cdot L^{-1}$ of cypermethrin (eAGRI 2022). After dilution with water (10 $mL \cdot L^{-1}$), it was applied as spray (Zahradník et al. 2023).

Trap trees were created from delimbed trunks of *Picea abies* (L.) H. Karst. (Norway spruce) trees felled in April 2023. The trunks were left in full length (length 29–34 m, diameter $d_{1,3}$ 34–38 cm) and underlain to be 0.2–0.3 m above the ground. The pheromone lure was fixed on the trunk surface (trunk diameter 24.5–31 cm) in the position 10 m from the stem base (i.e., 10 m from the stand edge, minimum allowed distance of pheromone according to Czech standard;ČSN 481000, 2005). Trap logs were underlain lying logs of *P. abies*, 0.2–0.3 m above the ground (length 4 m, stem diameter 27–30 cm) with the pheromone lure fixed on the surface in the middle of the trap log.

On May 2nd, 2023 and then May 30th, 2023, traps in both tree and log variant were set in triplicate at a mutual distance of 30–50 m and treated with 1% solution of Forester insecticide.

Because the insecticide application was carried out only 1 day before the assessment of *I. typographus* ethology, the experiment was carried out at maximum insecticide efficacy (Kula, Hrdlička, et al. 2024).

On May 4th, 2023, pheromone lures of IT Ecolure classic were fixed to the surface of trap trees and activated. Catch frames

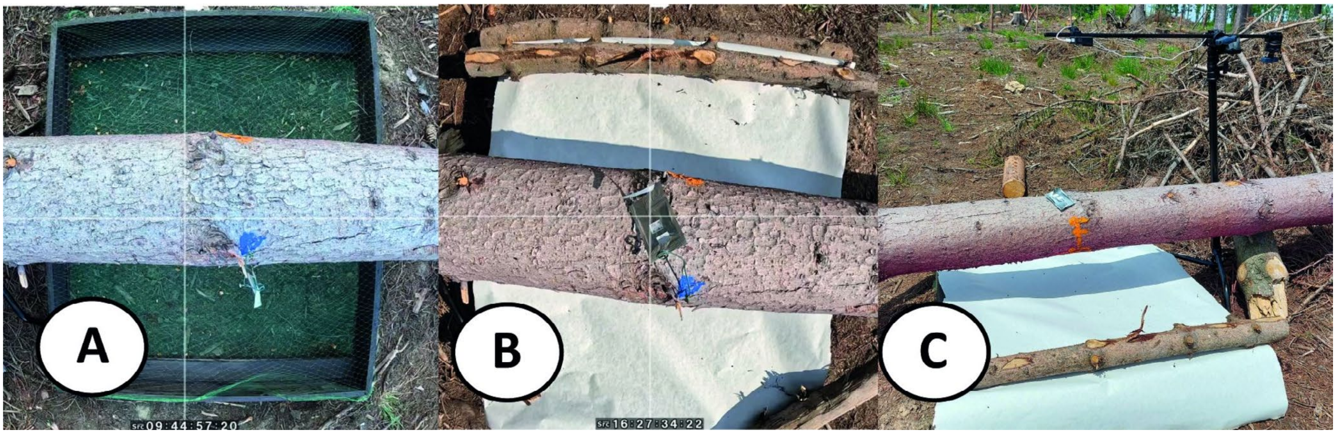

FIGURE 1 | Catch frame for control of dead *Ips typographus* imagines (A), camera shot for the following analysis of imagines movement (B), and camera position above the trap tree/log (C). [Colour figure can be viewed at wileyonlinelibrary.com]

(sized 1×1×0.15 m) were placed under the pheromone-treated stem section (2 m in length), with fine mesh at the bottom and covered with a net against birds for monitoring the fall of dead *I. typographus* imagines. On the control day (June 1st, 2023), the catch frames were covered with the white wrapping paper for the fast registration of dead imagines (Figure 1).

The observation of *I. typographus* activity took place on a clear-cut area sheltered on NE by the edge of spruce stand aged 110 years (mean height 31 m, mean diameter $d_{1.3}$ 35 cm, flat terrain, N 49°32′35″, E 16°11′48″, 618 m a.s.l.) near Bystřice nad Perštejnem (Czech Republic). In 2020–2023, a total timber amount felled due to bark beetle infestation in the stand was 1589 m^3 (Forest District Nové Město na Moravě).

Weather on June 1st, 2023 is characterised by data from the climatic station of Czech Hydrometeorological Institute (https://www.chmi.cz/?l=en) in Bystřice nad Perštejnem (N 49°31′27″, E 16°15′14″, 553 m a.s.l.) as follows: clear, sporadic cloud cover (cirrus), mean air temperature 17°C, mean relative air humidity 52%, total length of sunshine 12.5 h, average wind velocity 0.4 m·s^{-1}.

Air temperature on the site was measured using a Thermologger TMS (Tomst 2023) sensor hung 2 m above the ground in the adjacent spruce stand, with a measuring interval of 5 min. During the investigation, temperature varied in the range of 21°C–28°C from 10 to 18 h. The survey was focused on:

a. Intensity of *I. typographus* arrival to and departure from the poisoned traps (trees, logs).
b. Video recording for the following assessment of the frequencies of *I. typographus* imago arrivals and departures and the length of their stay on the treated surface.

2.1 | Intensity of *Ips typographus* Arrival Onto Poisoned Trap Trees and Logs

The survey was done on June 1st, 2023, from 10 to 18 h; the number of imagines was determined in the catch frames under individual trap trees and in 30 min intervals. Recorded dead and dying imagines were removed. Live imagines crawling on the trap above the catch frame (length 1 m) as well as therein were recorded during control intervals and then killed. Evaluation of imago presence on traps (3 trap trees, 3 trap logs) was done at the control time: the number of live individuals and the total number of dying and dead individuals were recorded. Mean air temperature was determined for each control sequence.

2.2 | Ethology of Imagines on the Treated Surface of Trap Trees and Logs

The behaviour of *I. typographus* imagines on the surface of poisoned trap trees and logs was scanned by two digital cameras GoPro HERO11 Black, San Mateo, USA (GoPro, https://device.report/manual/5524123), both with 4 K resolution, sensor Super 35 with sensitivity ISO 2000 and scan rate of up to 180 fps (XAVC-I). Data were stored in 4 K UHD (3840×2160 pixels)—50 fps. The recording allowed combining the occurrence of *I. typographus* imagines in the shot with the mean air temperature corresponding to a time sequence of 5 min. The scans were taken by a directly participating expert (F. Nádeníček, Department of Scientific and Pedagogical Information and Services, Mendel University in Brno).

One camera was fixed on a stand above the trap tree, the other one above the trap log. The camera position at about 75 cm above the stem surface allowed scanning the upper and one lateral side of the stem over a length of 1.4 m. The pheromone lure was on the upper side in the middle of the shot (Figure 1). Two video records were taken with a total length of ca. 15 h, observing the movement of beetles along the trap trees and logs from 10:00–17:50 h.

Video records were analysed in 5 min sequences in the entire camera frame for the total number of imagines occurring on the stem and the length of their stay on the stem. For the imagines that arrived at the stem, time was determined from arrival to departure or disappearance from the camera. For beetles with registered departure, the time of stay was determined from the moment of entering the camera shot. The length of stay was evaluated also for individuals entering the camera field of view and disappearing from the shot after a

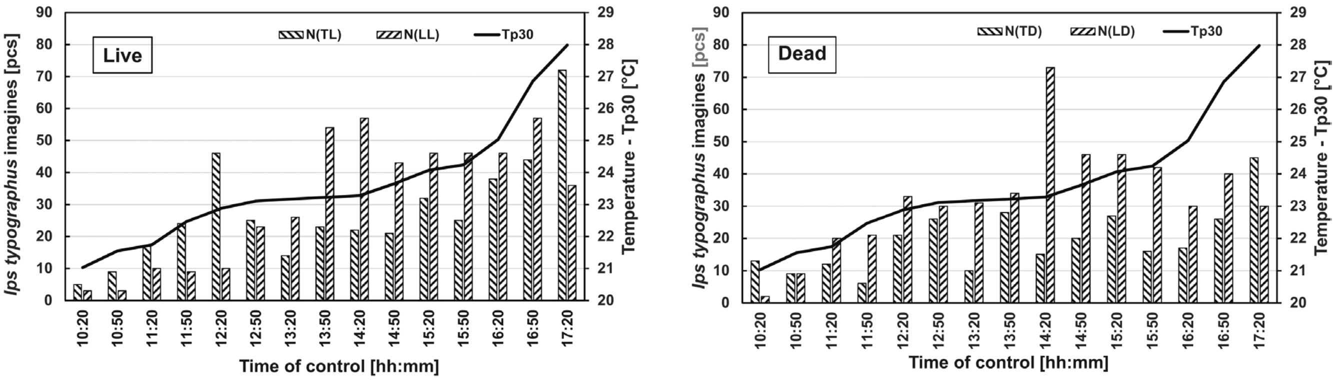

FIGURE 2 | Number of live *Ips typographus* imagines on trap trees—N(TL), logs—N(LL) and dead imagines in catch frames—N(TD) and N(LD) at the time of control with data on average air temperature (Tp30) for the control interval.

movement of varying length. The length of stay of all individuals seen in the camera field of view could not be evaluated at full extent; part of the stem was out of camera view. Thus, except for individuals with registered arrival and departure, the established time of stay on the trap tree or log is generally "underestimated". The analysis includes 194 sequences (5 min each) plus adequate mean air temperatures according to data from Thermologger TMS.

Behaviour of *I. typographus* imagines on the model trap tree and log was recorded by camera and then evaluated in the laboratory. Video record of the trap tree was taken at 9:30–17:55 h and analysed in 87 five-minute sequences, except the times between 11:05–11:35, 12:20–12:45, and 13:05–13:20 h when cards with reduced recording capacity were used. Video record of the trap log was taken with no interruption from 10:00–17:45 h and analysed in 93 five-minute sequences. The video record allowed exact evaluation of the behaviour of beetles, which had been up to now derived only from the field observations.

2.3 | Evaluation of Obtained Data

Data were evaluated using the MS EXCEL and STATISTICA (TIBCO Software Inc. 2018) applications using diagrams and change trend models. Variables related to the number of imagines were introduced for the evaluation: N(TL)—number of live imagines on the trap tree, N(TD)—number of dead imagines in the catch frame under the trap tree, N(LL)—number of live imagines on the trap log, N(LD) – number of dead imagines in the catch frame under the trap log, N(TST)—sum of arrivals to and departures from the trap tree, N(LST)—sum of arrivals to and departures from the trap log. Other variables were Tp(5) and Tp(30)—mean air temperatures in °C, measurement intervals 5 and 30 min, and *t*–time in seconds. Presented estimates of model trends and their parameters are statistically significant for $\alpha = 0.05$. Based on the coefficient of determination R^2 (%), evaluation of the model tightness was verbally expressed as follows: $R^2 \in (10, 25)$ – slight, $R^2 \in (25, 50)$ – remarkable, $R^2 \in (50, 80)$ – high, $R^2 > 80$ – very high.

While the incidence of dead adults in the catch frames was evaluated cumulatively every 30 min, the average value for a 5 min interval was used to express the interaction with live individuals. Since the analysis of live imago incidence on the trap trees and logs in the linked 5 min camera sequences cannot exclude an overlay in the occurrence of the same live beetles on the trap tree/log, the mean occurrence of live beetles on the trap tree/log was calculated in the control time of 30 min using the 5 min camera sequences. For the statistical evaluations, average numbers of live beetles on the trap tree/log in 5 min and average numbers of dead beetles in the catch frame for 5 min are used, obtained for the identical control intervals of 30 min, characterised by mean temperature.

3 | Results

In line with the methodology, the results are presented separately for (a) direct observation and evaluation of the reaction of *I. typographus* imagines (hereinafter imagines) on both types of poisoned trap trees/logs with the pheromone, day and temperature variability; (b) camera record of the occurrence of imagines on the trap trees/logs with the following laboratory assessment of *I. typographus* behaviour with respect to the incidence of imagines, length of stay, frequency of arrivals and departures of adults from the trap trees/logs during the day and to the changing air temperature.

3.1 | Direct Observation

3.1.1 | Intra-Day Variability

The day-long observation of *I. typographus* imagines arrival made it possible to determine the actual occurrence of live imagines on trap trees/logs and in catch frames as well as the number of dead imagines in catch frames. The whole-day observation (15 times a day, 30 min intervals) revealed uneven total effectiveness according to the number of dead imagines on all installed trap trees (37.4%) and logs (63.6%) at the place of pheromone lure position on the site. Individual trap trees and logs exhibited differences in the total number of caught imagines (live/dead) (trap trees: 241/122–21/31–155/138 pcs; trap logs: 113/85–135/99–221/303 pcs).

The arrival of adults onto the trap trees and logs differed during the day. Continual increase of arrival culminated between 16:00–17:30 and 14–16 h (Figure 2 Live), respectively. The incidence of dead imagines in the catch frames under trap trees fluctuated from 12:20 during the day after the initial increase; the total number of caught individuals was 291 pcs (37%). The number of dead imagines on trap logs was higher (487 pcs, 64%) and mortality culminated between 14 and 16 h (Figure 2 Dead).

3.1.2 | Temperature Variability

Temperature is an important variable affecting flight activity and swarming of bark beetles as well as their further development. Direct sunshine degree and current temperature fluctuations in the surroundings of trap trees/logs may cause partial deviations in the number of beetles on them and in catch frames (Figure 3).

The number of imagines on two trap trees was growing with increasing temperature, variability corresponding to temperature fluctuation. The estimated linear model of the trend was statistically significant ($p<0.05$). On the trap trees (TR), it corresponded to great closeness, determination index R^2(TR) = 73.80%, and on the trap logs (LO), it corresponded to significant closeness, R^2(LO) = 41.51%. The number of dead beetles in the catch frames under two trap trees was growing with the increasing temperature as well, variability corresponding to the temperature gradient around the trap trees. The estimated linear model of the trend was statistically significant ($p<0.05$), corresponding to great closeness under the trap trees, R^2(TR) = 56.43%, and to significant closeness under trap logs, R^2(LO) = 33.13% (Figure 3).

3.2 | Camera Surveillance

3.2.1 | Daily Variability

In the morning hours, 14 imagines on average (further avg.) occurred in the camera shot on the trap tree in each 5 min interval. In the intervals between 12–14 and 14–16 h, it was avg. Forty three imagines, and between 16 and 18 h avg. Sixty eight imagines (Figure 4—TR). The amount of beetles recorded on the trap log was lower, not exceeding 10 pcs (avg. 6) in the morning hours, later oscillating around 15 pcs and exceeding 20 pcs (avg. 36) only from about 16:30 h (Figure 4—LO).

3.2.2 | Effect of Temperature on the Incidence of Live Imagines on the Trap Trees/Logs

Activity of adults related to temperature was expressed by their occurrence in the short time interval of 5 min. On the trap tree, relatively low activity was recorded at the temperature range 21°C–22°C (<30 pcs of beetles), increasing up to 80 pcs at 23°C–24°C. From 27°C, the occurrence of beetles increased again to a daily maximum of >100 pcs. A general trend was

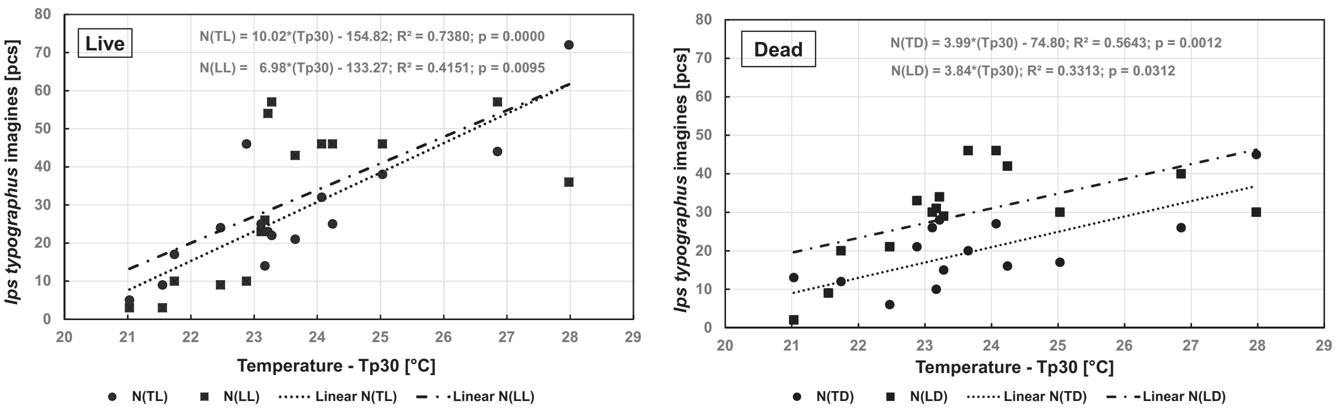

FIGURE 3 | Daily air temperatures (Tp30) and incidence of live *Ips typographus* imagines on trap trees—N(TL), trap logs—N(LL) and dead imagines in catch frames—N(TD) and N(LD).

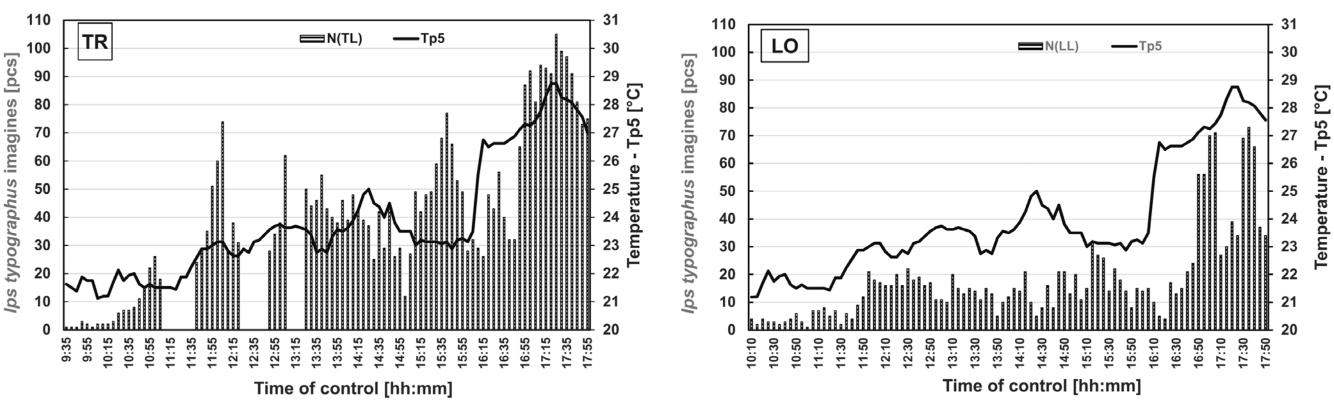

FIGURE 4 | Daily variability in the number of live *Ips typographus* imagines on the trap tree TR—N(TL) and trap log LO—N(LO) in 5 min camera shot sequences with data on air temperature (Tp5).

observed of the number of beetles increasing with the increasing temperature. The estimated model of the trend was linear, significant ($p < 0.05$), and with a great closeness, R^2(TR) = 56.43% (Figure 5—TR). On the trap log, the total number of recorded imagines was lower. At a temperature ranging from 21°C to 22°C, their incidence did not exceed 10 pcs, increasing with the growing temperature (23°C–24°C). Further increase of imago activity was related to temperatures > 26.5°C and led to a daily maximum of 70 pcs. The number of imagines was generally increasing with the increasing temperature. The estimated model of the trend was linear, significant ($p < 0.05$), with a limit of great closeness, R^2(LO) = 49.99% (Figure 5—LO).

3.2.3 | Effect of Temperature on the Incidence of Live Beetles on Trap Trees/Logs and Dead Beetles in Catch Frames

In relation to temperature, the average incidence of live imagines was studied on the surface of both trap tree/log and in catch frames. A selected time interval was 30 min. At temperatures ranging from 21°C to 25°C, the number of live imagines on the trap tree fluctuated (maximum being observed at about 23°C, > 40 pcs), while 90 pcs were confirmed at temperatures above 27°C. The obtained data are similar to the direct field observation with the variability corresponding to the temperature gradient. Temperature increase supports the activity of beetles. The estimated model of the trend was linear and significant ($p < 0.05$), with a high degree of closeness, R^2(TR) = 51.27%. The amount of dead beetles in the catch frame was small, not exceeding 5 pcs; the effect of temperature was not demonstrated (Figure 6—TR). On the trap log, the number of imagines was increasing with some smaller fluctuations; the temperature gradient did not show. It was lower compared to the trap tree, with a maximum of about 50 pcs. The estimated model of the trend was linear and significant ($p < 0.05$), with a very high degree of closeness, R^2(LO) = 81.84%. Compared to the trap tree, the number of dead beetles in the catch frame was higher but not exceeding 10 pcs; the effect of temperature was not demonstrated (Figure 6—LO).

3.2.4 | Incidence of Live and Dead Images on the Trap Trees/Logs

The video record shows a significant difference between the detected number of live imagines occurring on the trap trees/logs and the number of individuals found in the catch frames. The results support a hypothesis about the significant frequency of beetles departing from the surface of trap trees/logs. On the trap tree, the number of caught dead beetles was growing with the increasing number of beetles on the surface. The estimated

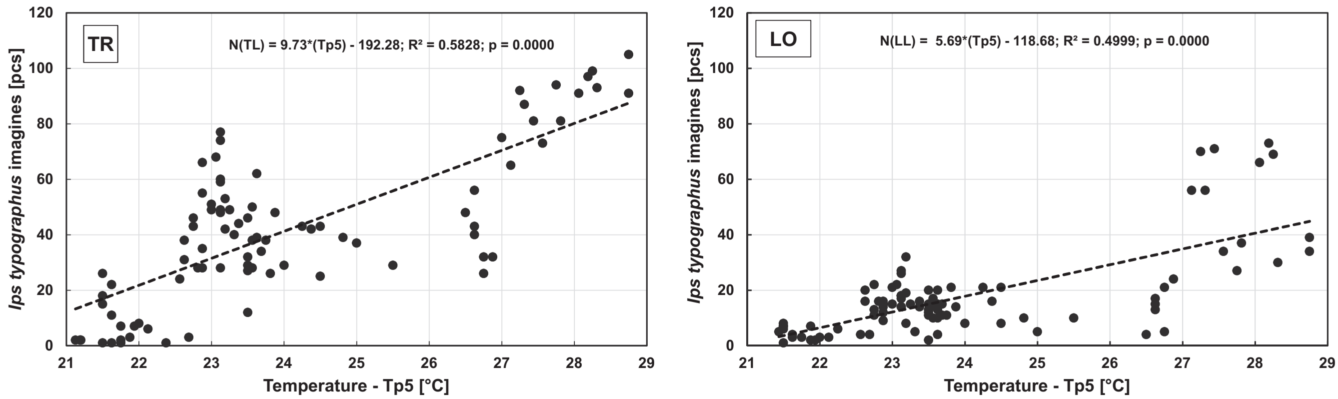

FIGURE 5 | The number of live *Ips typographus* imagines as a function of temperature (Tp5) in 5 min control sequences recorded by the camera above the trap tree—TR—N(TL) and trap log—LO—N(LL).

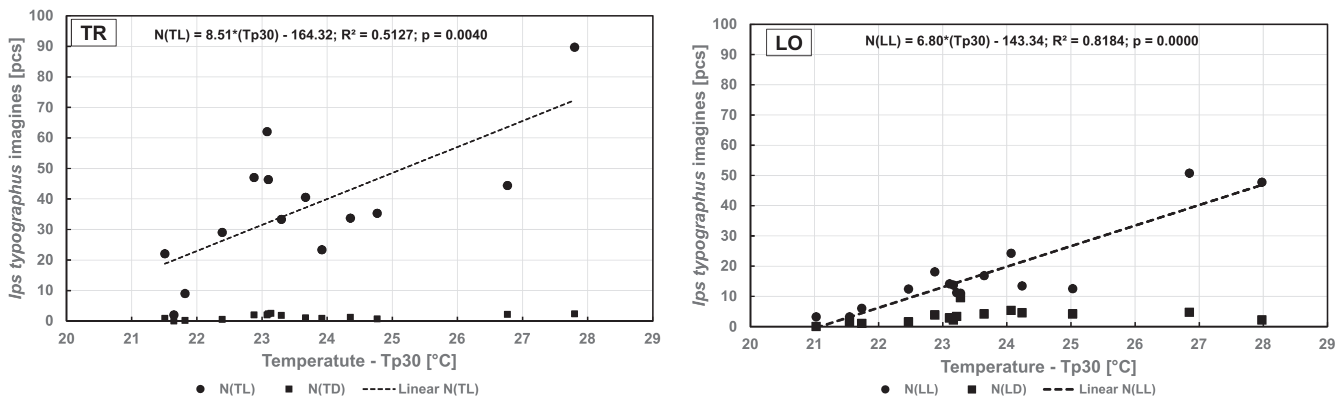

FIGURE 6 | The number of live *Ips typographus* imagines N(TL), N(LL) on trap trees—TR) and trap logs –LO and dead imagines N(TD), N(LD) in corresponding catch frames as a function of average air temperature (Tp30) in control terms according to camera records (trend for N(TD) and N(LD) non-significant).

model of the trend was linear, significant ($p < 0.05$), with a high degree of closeness, R^2(TR) = 67.61% (Figure 7—TR). On the trap log, the changing trend between the number of captured dead imagines and the number of imagines on the surface of the trap was not evident (Figure 7—LO).

3.2.5 | Effect of Temperature on the Length of Imago Stay on the Trap Tree/Log

Length of stay and movement along the trap trees/logs create preconditions for further contamination and following mortality after departure. The length of stay was related to increasing flight activity in dependence on the increasing air temperature. Increased imago activity reflected in a shortened stay on the trap tree/log; at temperatures above 23°C, the time did not exceed 50 s. The estimated model of the trend of changes on both traps was non-linear, significant ($p < 0.05$), with a great closeness on the trap tree, R^2(TR) = 51.74%, and significant closeness on the trap log, R^2(LO) = 46.30% (Figure 8).

3.2.6 | Effect of the Number of Live Beetles on the Length of Stay on the Trap Tree/Log

The assumption that spatial stress from increased abundance of occurring imagines can affect the length of stay of imagines on the surface was confirmed in both trap trees/logs when the growing number of imagines significantly shortened the length of their stay. On the trap tree surface, the time of stay exceeded 100 s for up to 10 imagines, being considerably lower for 20 pcs, usually up to 50 s. The situation on the surface of the trap log was more complicated. With the number of beetles up to 5 pcs, the length of their stay on the surface ranged from 40 to 100 s and significantly fluctuated (Figure 9). The estimated model of the trend of changes on both trap trees/logs was non-linear, significant ($p < 0.05$), asymptotically tending to very low numbers. On the trap tree, it had a great closeness, R^2(TR) = 72.21%; on the trap log significant closeness, R^2(LO) = 31.23% (Figure 9).

3.2.7 | Effect of Temperature on the Frequency of Imagines Arriving to and Departing From the Trap Tree/Log

The frequency of arrival to and departure from the two traps (tree/log) in relation to temperature can be characterised similarly as in the number of imagines affected by temperature (Figure 5). The frequency fluctuated at the temperature range of 21°C–24°C and was observed to increase at 23°C. Between 24°C and 27°C, it stagnated at a level of 5 imagines and was growing on the trap tree at a temperature above 28°C, when it exceeded the level of 20 imagines. In the trap log, > 25 pcs of imagines were found at temperatures above 27°C. The estimated model of the trend of

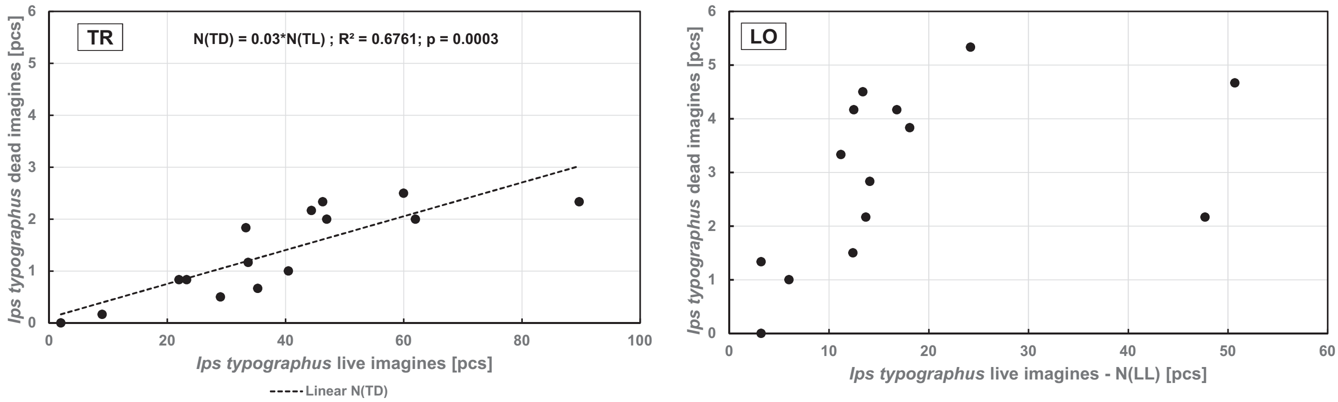

FIGURE 7 | The number of live *Ips typographus* imagines on the trap tree—TR and trap log –LO against dead imagines found in the corresponding catch frames, camera record (trend for LO non-significant).

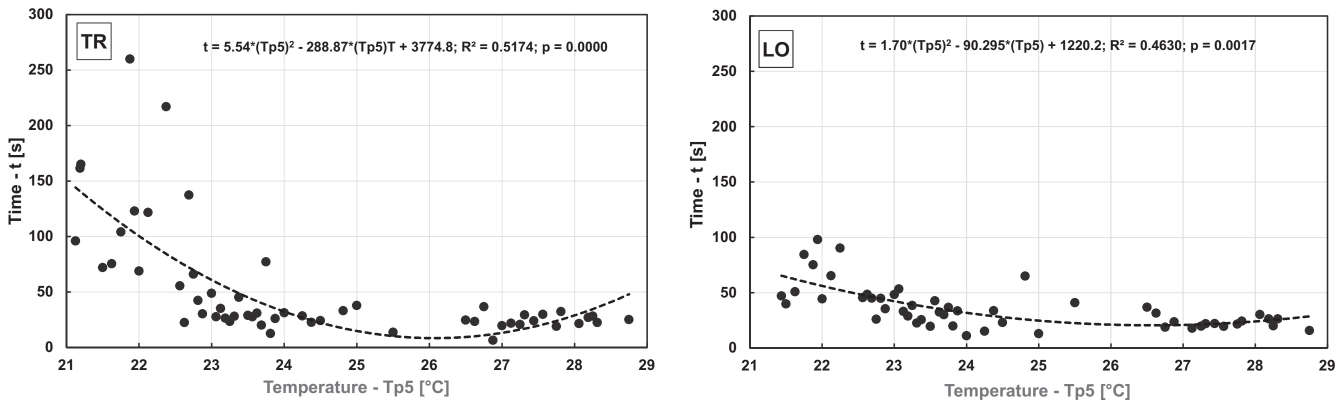

FIGURE 8 | The movement of *Ips typographus* imagines along the surface of trap tree—TR and trap log—LO as a function of temperature (Tp5), camera record.

changes on both traps was linear and significant ($p < 0.05$). Its closeness on the trap tree was slight, R^2(TR) = 21.95%, and significant on the trap log, R^2(LO) = 31.51% (Figure 10).

3.2.8 | Effect of the Number of Imagines on the Trap Tree/Log and the Frequency of Their Arrival to and Departure From It

The frequency of arrival to and departure from the trap tree increased with the amount of beetles present thereon. The behaviour of imagines was more apparent on the trap log. The estimated model of the trend of changes on the two traps was linear and significant ($p < 0.05$). On the trap tree, it exhibited significant closeness, R^2(TR) = 45.71%, and on the trap log great closeness, R^2(LO) = 76.21% (Figure 11).

4 | Discussion

In the period of the epidemic stage of population dynamics when bark beetle exhibits high population density, even healthy trees where the mortality is high are infested (Christiansen et al. 1987). In this period, extraordinarily efficient defensive measures have to be adopted in order to reduce the occurrence of *I. typographus* adults and to prevent the disintegration of spruce stands. Apart from the removal of material attractive for the bark beetle development and sanitary felling (Wermelinger 2004; Fettig and Hilszczański 2015), the system of integrated pest management includes also the targeted catching of beetles with the use of pheromone-baited traps of different types and attractants (Raty et al. 1995; Blaženec et al. 2021; Kuhn et al. 2022).

A number of authors corroborated not only the significant effectiveness of catching the pests using various types of trap trees/logs but also their variability in dependence on the location and current conditions in the stands (Schlyter 1992; Duelli et al. 1997; Franklin and Grégoire 2001). This suggests that the use of baited poisoned trap trees/logs should not be completely ruled out. The principle is based on the intoxication of non-barked timber (Faccoli and Stergulc 2008; Lubojacký and Holuša 2011, 2013, 2014) with attractiveness secured by specific pheromone. Unlike the baited slot traps from which the caught bark beetles cannot escape, it was observed that imagines of *I. typographus* leave the surface of poisoned trap trees/logs and poisoned nets (authors´ own observation and pers. comm.) and die outside them due to contamination (Raty et al. 1995; Skrzecz et al. 2015). It is not surprising that a live tree treated with insecticide and lured with pheromone has a higher catch of beetles than the pheromone trap Theyshon 1st flight 2.5–8.5 times and 2nd flight 3.5–32 times (Raty et al. 1995). Thus, the method of poisoned trap trees/logs can be used as a defence (Grégoire et al. 1997). A study focused on

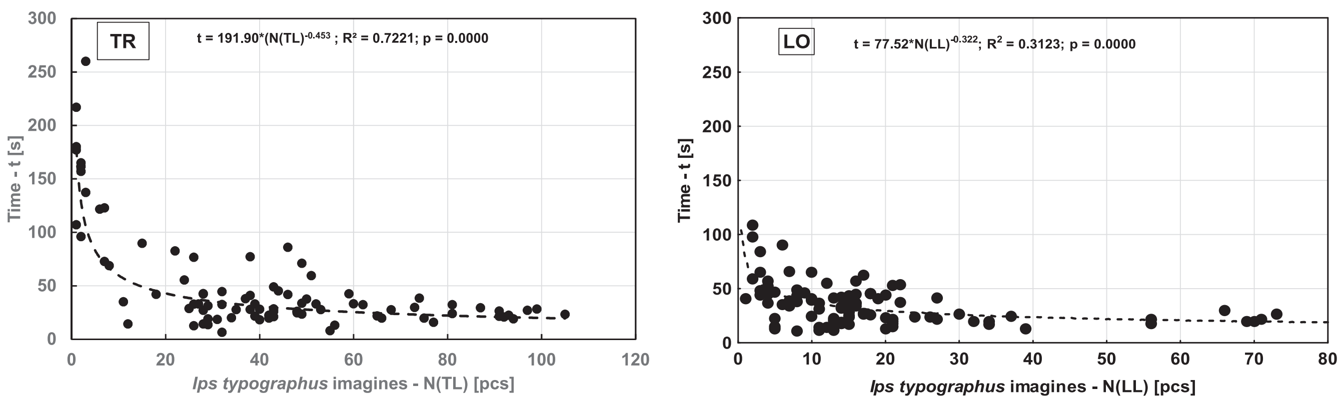

FIGURE 9 | Effect of the number of *Ips typographus* imagines on the length of their stay on the surface of trap tree– TR and trap log –LO, camera record.

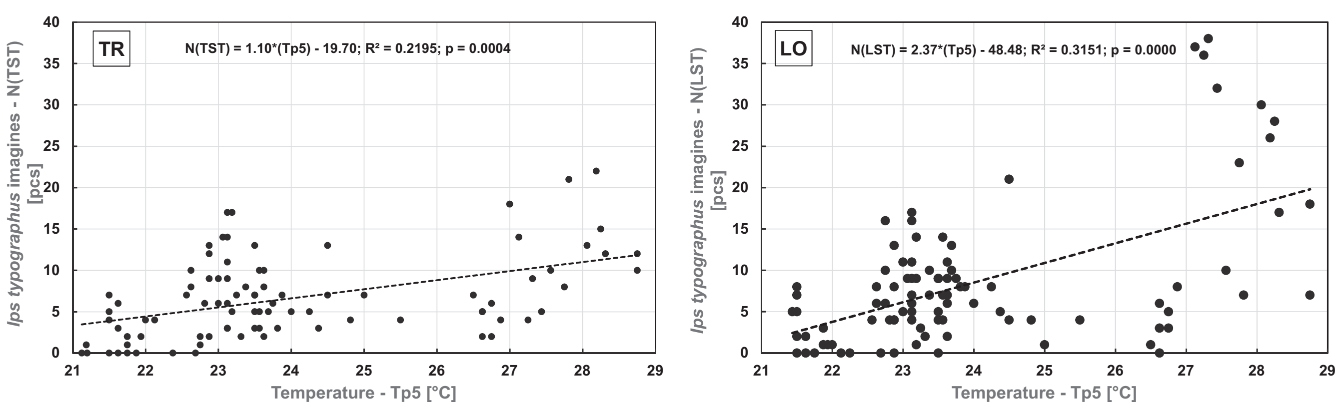

FIGURE 10 | The frequency of *Ips typographus* arrival and departure to/from the surface of the trap tree—TR—N(TST) and trap log—LO—N(LST) as a function of temperature (Tp5), camera record.

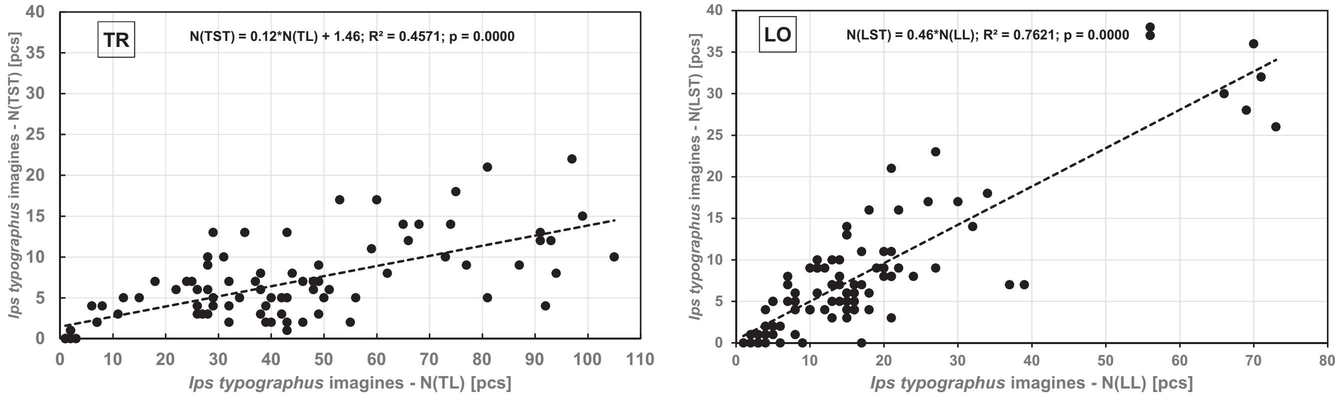

FIGURE 11 | The frequency of *Ips typographus* imagines arrival to and departure from the trap tree—TR—N(TST) and trap log—LO—N(LST) against their amount on the trap, camera record.

different forms of poisoned trap trees baited with IT Ecolure pheromone confirmed high efficiency of catching the pest imagines in poisoned trap trees, 4 m long logs. Efficiency of this defensive method depends on the quality of intoxication and on the sufficiently long contact of bark beetles with the treated surface (Kula, Holuša, et al. 2024; Kula, Hrdlička, et al. 2024). Raty et al. (1995) demonstrated in the laboratory that the length of detected movement of *I. typographus* adults along the poisoned trap tree/log (2 min 40 s) causes a 100% death even after departure from the trap.

To further broaden the knowledge base, a field survey was conducted to specify the behaviour of *I. typographus* adults on poisoned trap trees/logs baited with IT Ecolure pheromone using a video camera. The record was made on June 1st, 2023, from 9:30 to 18:00 h, in time corresponding to the daily flight activity of imagines (Funke and Petershagen 1994) and at an air temperature of 20°C–30°C, considered optimal for swarming (Funke and Petershagen 1994; Lobinger 1994). Regarding the originality of the chosen procedure, some conclusions from data analysis cannot be compared with those of other authors.

The trend of increasing occurrence of live beetles with the growing air temperature, culminating in the afternoon hours, observed in the field, was corroborated by the estimated linear models. The fluctuation in the amount of imagines is related to their sensitivity to current sunshine intensity and temperature during the day. Such a behaviour of *I. typographus* is in line with conclusions of Lobinger and Skatulla (1996). According to Hinze and John (2020), most *I. typographus* were caught on the hottest day (max. temperature of 33.4°C) of the observation period (mean air temperature 19.2°C), suggesting that its ability to find hosts and mass flight is not compromised by increased thermal conditions. The number of dead beetles in catch frames copied the trends of occurring live beetles.

Daily temperature variability and the effect of temperature on the activity of *I. typographus* adults captured by camera in the scanned trap tree/log section were in accordance with the direct observation in the field. Although the air temperature was increasing during the day, its course was fluctuating. The amount of beetles related to temperature on both trap trees/logs formed clusters at lower and higher temperatures. However, temperature changes had no effect on the number of dead beetles in the catch frames. On the trap tree, the number of caught dead imagines corresponded to the number of observed live imagines (linear estimate); on the trap log, such a relationship was not found.

The air temperature was determined in the shade of the growth, not directly on the surface of the bark on the trap. Monoterpene emission in conifers is a function of vapour pressure within plant tissues, which is controlled by air temperature and concentration within the tissues (Lerdau et al. 1997). The cooling effect of sap flow on the phloem of healthy trees is sufficient to keep temperature-dependent emissions of terpenes below those of stressed trees with reduced transpiration. In a stressed tree with diminished sap flow, on the other hand, temperatures and thus emissions will be higher than in healthy neighbouring trees, which could identify weakened trees to beetles and make them attractive (Hietz et al. 2005). In traps made from felled logs, sap flow is interrupted, and the bast and wood continuously dry out (Kula and Šotola 2017; Kula, Holuša, et al. 2024). Ethanol content was higher in rain-wetted cut logs, where the diffusion of oxygen was reduced by the high bark water content, than in dry logs. Bark beetles consequently preferred wetted logs (Kelsey and Gladwin 1999). There is no study focused on the process of emission of monoterpene under the influence of temperature from poisoned traps, where commercial pheromones provide attractiveness.

Natural behaviour of imagines in the phase of looking for and flying onto a live spruce trunk is characterised by the frequently changing direction of motion and by detecting a proper place for the entrance hole (Paynter et al. 1990). Trunk colonisation can be regulated by sex-specific reactions to quantitative changes of released natural pheromones: males avoid higher concentrations and move to other places, which extends the area of aggregation (Byers 1984).

On the baited poisoned trap tree/log with the increased concentration of IT Ecolure pheromone, rectilinear movement of imagines predominated without stops and detection of places suitable for establishing galleries. Arrival and departure of beetles was scanned by a camera, but most beetles were settling on the trap tree/log outside the camera shot (> 0.7 m from the lure).

Only 10%–15% of individuals reached the pheromone position, which they were subsequently leaving. A majority of imagines passed the pheromone position with no reaction. The day-long video record showed not even a single "attempt" of a male to gnaw an entrance hole, which excluded natural communication in the population conditioned by males taking food and by the release of attractants and sex hormones (Birgersson et al. 1984). The bark structure, which can affect the process of searching (Byers 1984), was not disturbed on the poisoned trap trees/logs.

The phase of search on a live, uncontaminated tree lasts on average 180s for males and 240s for females, with a third of individuals leaving the tree (Byers 1984; Paynter et al. 1990), which is related to the natural control of final abundance (De Jong and Sabelis 1988; Schlyter and Anderbrant 1989). Obtained data on baited poisoned trap tree/log showed the time of stay between 40 and 100s. The length of stay was negatively affected by increasing temperature.

Pheromone lure on the poisoned trap tree/log can simulate a heavily occupied environment and a reason for departure (Paynter et al. 1990), as well as uncreated nuptial chambers (Schlyter and Löfqvist 1986). Their study showed that increased abundance of live imagines on the trap tree/log could be a cause of the rapidly decreasing length of stay on the trap tree/log.

A reason for leaving the trap tree/log can also be the detection of a contaminated surface, which prevents the creation of entrance holes by males. The repellent effect of the active substance of deltamethrin on the bark beetle *Phloeotribus scarabaeoides* Bern was determined (Rodríguez, Campos, et al. 2003; Rodríguez, Peña, et al. 2003). The applied insecticide contained cypermethrin as an active substance, and we did not observe such a repellent effect in the behaviour of *I. typographus*. Acquired results demonstrated that increased air temperature (> 27°C), when the flight activity of *I. typographus* is culminating, contributed to the frequency of arrival and departure of beetles to/from the poisoned trap tree/log. The frequency of their departure from the trap tree/log linearly increased with the increasing abundance of beetles on the trap tree/log. Yet, the intoxication of leaving imagines is a precondition for their death (Raty et al. 1995; Kuhn et al. 2022).

Direct mortality on poisoned trap trees/log was 18%–21%. Taking into account the finding (Kula, Hrdlička, et al. 2024) that imagines of *I. typographus* moving along the surface treated with Forester insecticide (even 3weeks after application) for 30–90s die within 12h at 80%–90%, the efficiency of poisoned trap trees/logs significantly increases (by 40%–60%), thanks to individuals leaving the trap tree/log. The number of dead beetles depended on their abundance on the trap tree/log, not on the temperature gradient.

The toxicity of insecticides is influenced by abiotic factors (temperature, precipitation and light) and biotic factors (chemical uptake, metabolism) of the target organisms to which the insecticides are applied (De Vries and Georghiou 1979; Weston et al. 2009; Laetz et al. 2014). At high temperatures, the chemical binding of pyrethroid insecticides is reduced (Vijverberg et al. 1983), including cypermethrin applied to free-living herbivorous insects (Jagers op Akkerhuis et al. 1999). In cryptic bark beetles, achieving efficacy is more difficult. Pajares and Lanier (1989) reported that cypermethrin was very effective in killing elm bark beetles, but Jin and Webster (1998) demonstrated that cypermethrin does not penetrate the bast parts, where the developmental stages are located. The aim of insecticide application is primarily to protect the wood from bark beetle attack. It is therefore important to apply insecticide to the surface of the trunks under temperature conditions recommended by the manufacturer (not higher than 25°C) and according to climatic conditions and the purpose of the application to restore the toxicity of the surface (Kula, Hrdlička, et al. 2024). With the expected formation of boreholes by bark beetles (penetration into the bark), the effectiveness is much longer than with poisoned traps aimed at achieving death due to the mere movement of the adults over the contaminated surface.

Consistent with the hypothesis, a deviation was recorded in the behaviour of *I. typographus* on the poisoned trap tree/log in the space rich with pheromone where imagines exhibited direct movement, not demonstrating search of places for making entrance holes; their contact with the pheromone lure was sporadic, and the predominating movement from the lure or out of its position could have been caused by increased pheromone concentration inducing a need to look for space with lower "competition." In contrast with pheromone traps from which there is no escape, poisoned trap trees/logs allow the insects to fly away.

The cause of increased departure of beetles was not only the increasing temperature which supports their flight activity but also the increased abundance of imagines on the trunks. Direct mortality of beetles on the poisoned trap tree/log is a reflection of abundance, not temperature. Thus, the length of movement along the trap tree/log is shortened, which could influence the mortality of departing individuals if their contact was shorter than 30s. After a contact with poisoned surface longer than 30s, direct mortality of imagines (18%–21%) increased due to indirect mortality of leaving imagines. At the time of gradation, poisoned trap trees/logs can be applied to eliminate *I. typographus* effectively.

Author Contributions

Kula Emanuel designed the study and participated in fieldwork, data collection, sample analysis, and their interpretation. **Hrdlička Petr** participated in sample analysis, statistical evaluation, and interpretation. They both wrote and edited the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The dataset has been deposited in the Dryad data repository. https://datadryad.org/stash/share/1B15DFpJWrt9HsiKOUeqZzNBtqY1vTes3QGnNnDU0RM; https://doi.org/10.5061/dryad.zcrjdfnpt.

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