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Evaluation of electronic pheromone trap capture conditions for *Ips sexdentatus* with climatic and temporal factors

Gonca Ece Özcan · **Hakan Şükrü Tabak**

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Abstract Controlling forest pests to maintain the sustainability of forests and ecosystem balance is one of the interests of modern forestry. In the evaluation of damage risks associated with forest pests, pheromone traps attract attention by providing early warnings. With the development of these traps in line with modern technology, more reliable data are obtained; these data are important in the identification and planning of pest management. In this study, a pheromone trap with electronic control unit was tested under field conditions. The capture of adult *Ips sexdentatus* under natural conditions during 103 days of the flying period was evaluated; 97.2% of the beetles captured in the trap were the target species. The comparison of the number of beetles recorded by the trap and manual counts revealed that the trap worked with an error margin of approximately 4%. However, no statistically significant difference was noted between these two counting methods. During the study, 59% of the total beetles were captured between May 27 and June 25. The average temperature at the period of the capture was 20.09 °C, average humidity was 66%, and average wind speed was 2.9 m/s. Of the captures, 73.9% occurred in the temperature range of 15–24.9 °C, 61.1% occurred in humidity range of 61–90%, 89.6% occurred at a wind speed of 0.3–5.4 m/s, and 77.3% occurred within the period from sunrise to sunset. When these four parameters were evaluated together, the most strongly associated parameter was daylight, followed by temperature, wind speed, and humidity.

Keywords Forest pest · Six-toothed bark beetle · Crimean pine · Precision forestry · Pheromone monitoring

Introduction

Forest pests are one of the important factors directly or indirectly affecting forest economy, ecosystem services, biodiversity, and sustainable ecosystem management (Choi & Park, 2019; Flint et al., 2009; Rosenberger et al., 2012; Seidl et al., 2018). Among these pests, bark beetles (Coleoptera: Curculionidae, Scolytinae) could have strong and irreversible adverse effects on forest productivity and ecosystem dynamics owing to their long-term influences as a result of epidemics of different species (Anderegg et al., 2015; Grégoire et al., 2015; Hlásny et al., 2019; Marini et al., 2017; Näsi et al., 2018; Progar et al., 2009; Samman & Logan, 2000; Sharma, 2016).

G. E. Özcan (✉)
Faculty of Forestry, Department of Forestry Engineering, Kastamonu University, 37150 Kastamonu, Turkey
e-mail: goncaece@kastamonu.edu.tr

H. Ş. Tabak
Institute of Science, Kastamonu University, Forest Engineering Program, 37150 Kastamonu, Turkey
e-mail: s_hakan_1987@hotmail.com

Dendroctonus, *Ips*, and *Scolytus* genera of bark beetles are the primary causes of tree deaths (Morris et al., 2017). The six-toothed pine bark beetle, *Ips sexdentatus* (Boerner) (Coleoptera, Curculionidae, Scolytinae), which is exclusive to Eurasia, generally attacks pine (*Pinus nigra, P. pinaster, P. heldreichii, P. sylvestris*) and spruce (*Picea orientalis*) species in Turkey and other countries (Agbaba & Celepirovic, 2008; Bueno et al., 2010; Jactel & Gaillard, 1991; Jeger et al., 2017; Morris et al., 2017; Özcan et al., 2011; Özcan, 2017 Sarıkaya & Avci 2011). This species was first identified in 1928 in the forests of Turkey and is considered one of the most dangerous forest pests in the conifer forests of the country (Bernhard, 1935; Beşceli & Ekici, 1969; Oymen, 1992). Although *I. sexdentatus* primarily prefers weakened or dead trees, it could also attack healthy trees as a result of mass outbreaks (Fernández, 2006; Jeger et al., 2017; Pineau et al., 2017; Rossi et al., 2009), and in case suitable conditions arise in the areas it spread, it can cause an epidemic (Bracalini et al., 2021). Monitoring these destructive beetles, identifying both damage risk and management strategies, as well as containing the target species are necessary measures for the protection of forests (Choi & Park, 2019; Schowalter, 1986; Sharma, 2016). Therefore, protecting forests from these destructive pests is among the primary objectives of forest management.

Pheromone traps are widely used to monitor and control populations of bark beetles in integrated pest management, which involves applying mechanical, chemical, cultural, biological, and biotechnical methods combined to minimize environmental risks (Baker & Health, 2005; Donaldson & Seybold, 1998; Galko et al., 2016). These traps are one of the few effective methods of controlling the populations of bark beetles (Fettig & Hilszczański, 2015), and they are widely used as monitoring tools. Real-time monitoring features of new generation traps enable obtaining useful information against pests such as early warning (Sciarretta & Calabrese, 2019). Pheromone traps help to make observations on the density and distribution of target species' populations, to obtain specific information on their flight activities, and, to some extent, to detect early warnings (Baker, 2008; Galko et al., 2013; Holuša et al., 2012; Lindelow & Schroeder, 2001; Özcan et al., 2011; Sciarretta & Calabrese, 2019; Wermelinger, 2004). Predicting flight activities based on abiotic factors, providing detailed information about the population dynamics of pests, and developing monitoring techniques contribute to integrated pest management (Chen et al., 2020). Pest management tends to develop new approaches as bark beetles are likely to pose more risks to forests in the future with changes that may occur owing to several factors, especially climate change (Boyd et al., 2013).

These beetles adversely affect the sustainable forest management (Akyol & Tolunay, 2006; Black et al., 2010). Sustainable management requires precision forestry principles that aim at minimizing environmental damage while ensuring optimum yield from forests using analytical modeling and measurement techniques (Gulci, 2014). In line with these principles, modern forestry, keeping up with technological developments, and the improvement of control strategies and methods with innovative approaches to management pests rise to prominence (Özcan et al., 2016). Currently, pheromone traps used in forestry do not determine data on the temporal and climatic conditions under which beetles are captured (Özcan et al., 2014). Therefore, pheromone traps with the electronic control unit (ECU) have been designed, which aim to expand the current purposes of pheromone traps (Çiçek et al., 2016, 2018; Özcan et al., 2014, 2016).

It is important to explain the biology and behavior of bark beetles within specific time intervals based on the climatic conditions effective at those times. Assuming that the increase in temperatures due to climate change will increase the reproductive capacity of bark beetle (Wermelinger & Seifert, 1999), determining the parameters that affect the flight may also help to predict the related risks. Pawson et al. (2017) stated that it is difficult to predict outbreaks because it has not been completely explained how temporal and climatic parameters affect the flight of beetles. In the present study, the effects of climatic and temporal parameters on the flight of the target species were investigated, considering the strong effect of beetle outbreaks on forest resources. Therefore, field studies were performed with an ECU pheromone trap, for which the counting success was quite high in the workshop trials (Özcan et al., 2018), and the capture of adult *I. sexdentatus* and performance of the trap in the natural environment were evaluated.

Material and method

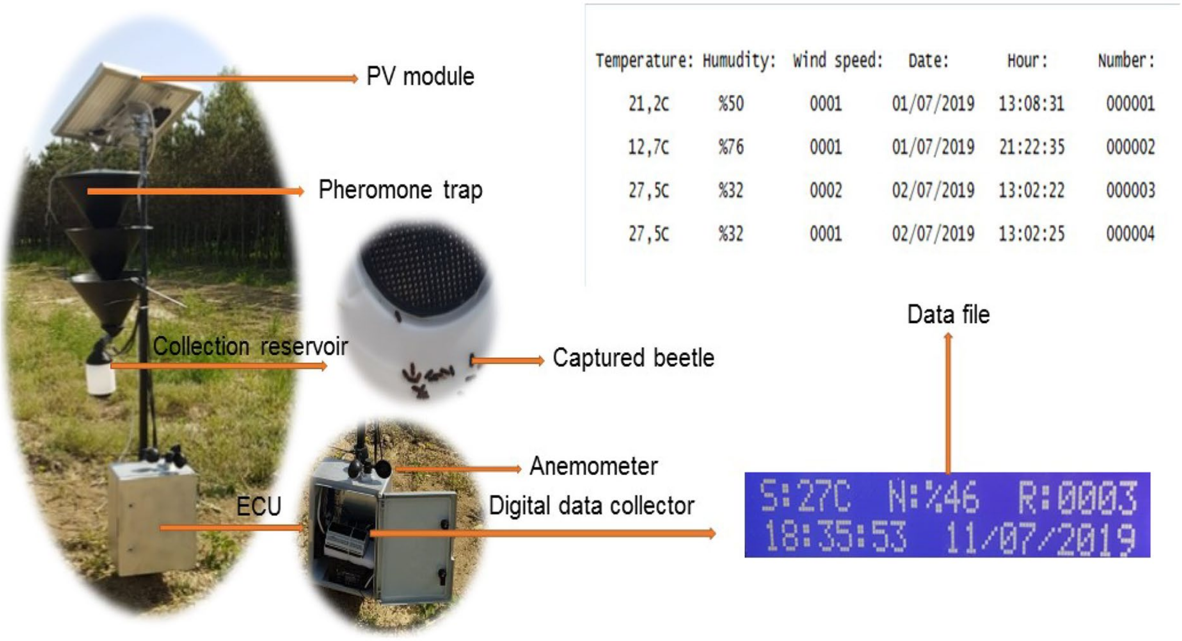
The pheromone trap with electronic control unit was set in an open area in Daday, Kastamonu Province in northwestern Turkey. The test site is a Crimean pine forest (*Pinus nigra* J.F. Arnold subsp. *pallasiana* (Lamb.) Holmboe) where damage caused by *Ips sexdentatus* is observed every year. *I. sexdentatus* pheromone with 60 mg of ipsdienol per dose was used in the trap with the trademark Tripheron® Ipssex®. Pheromone baits were replaced every 4 weeks. The time of capture within the flying period (i.e., year, month, day, and hour) of the adult beetles and temperature, humidity, and wind speed at the time of capture were recorded. Thus, the performance of the trap was evaluated using the data on the capture intervals of the target species during the day; the time when the most numbers of captures occurred; differences in capture rates; daylight; and temperature, humidity, and wind parameters affecting the capture.

Data collections

Under natural conditions, the ECU pheromone trap was continuously monitored between May 27, 2019, and September 6, 2019. In this 103-day period, owing to the technical features of the pheromone trap, the number of the adult beetles captured in the trap and time of capture (i.e., day, month, and hour), as well as temperature, humidity, and wind speed at the time of capture, was recorded in the data file on a microSD card. These files were backed up by transferring them to the computer environment every 15–20 days (Fig. 1). To test the success of electronic counting of the trap, the collection reservoir was emptied daily, provided that the hours were kept constant, and the captured beetles were counted manually as well. In the event that adults of the main predator, *Thanasimus formicarius* (L.) (Coleoptera: Cleridae), they would be released back to the forest.

Data set

Each of the parameters measured at the moment of capture was grouped separately and categorized. Temperature and humidity were divided into five and eight groups, respectively, depending on the values at which the highest and lowest capture occurred; the wind speed was divided into six groups according to the Beaufort wind scale (Wallbrink & Koek, 2009); the sunrise–solar noon–sunset time intervals were divided into three groups to evaluate the effect



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Temperature: Humudity: Wind speed:  Date:       Hour:     Number:
  21,2C       %50        0001      01/07/2019  13:08:31   000001
  12,7C       %76        0001      01/07/2019  21:22:35   000002
  27,5C       %32        0002      02/07/2019  13:02:22   000003
  27,5C       %32        0001      02/07/2019  13:02:25   000004
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S:27C  N:%46  R:0003
18:35:53  11/07/2019
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Fig. 1 Equipment and working mechanism of the pheromone trap with electronic control unit

Table 1 Groups and class limit values created according to the parameters

Groups	Humidity (%)	Wind speed (m/s)	Temperature (°C)	Daylight
I	20–30	0–0.2 (calm)	7.42–14.99	Sunrise–solar noon
II	31–40	0.3–1.5 (light air)	15–19.99	Solar noon–sunset
III	41–50	1.6–3.3 (light breeze)	20–24.99	Sunset–sunrise
IV	51–60	3.4–5.4 (gentle breeze)	25–29.99	
V	61–70	5.5–7.9 (moderate breeze)	30–37.12	
VI	71–80	8.0–10.7 (fresh breeze)		
VII	81–90			
VIII	91–93			

of daylight (Table 1). Differences in solar movements have been taken into account in grouping the time intervals for daylight. Accordingly, as sunset occurs 1 h earlier after August 5 and sunrise occurs 1 h later after August 22, the data have been arranged according to these differences.

To evaluate the times when beetles were or were not captured, as well as to study the climatic, a total of 103×24=2472 unit data sets were created for a total of 24 h every day for 103 days. Average temperature, humidity, and wind speed recorded by the ECU trap for each unit range were checked to data provided by the meteorological station situated 135 m upper the study area.

Statistical analyses

The data were statistically analyzed using IBM SPSS Statistics 23. Variance analyses, as well as descriptive statistics comprising the smallest and largest values and percentages, were used to evaluate the data on the number of beetles captured in the trap; time of capture; and temperature, humidity, and wind speed at these times. As the numbers of *I. sexdentatus* recorded by manual and ECU pheromone trap did not demonstrate normal distribution, the differences between the two groups were checked with Mann–Whitney *U* test. The statistical differences among the average temperature, humidity, and wind speed at the time of capture and non-capture were analyzed using Mann–Whitney *U* test, and daylight was evaluated using the Kruskal–Wallis test. Owing to the categorical nature of the data, the Chi-square independence test was used for non-parametric tests to statistically reveal the entrapment status of *I. sexdentatus*, depending on the temperature, humidity, wind speed, and daylight. The strength of the parameters on the effects of being caught was also interpreted with the Phi value.

Results

According to manual counts, a total of 1622 beetles were captured in the ECU pheromone trap. Of these beetles, 97.2% was *I. sexdentatus*, which was the target species; 1.7% was *T. formicarius*, which are the predators of the species; and 1.1% was other insect species. Although this trap records all the beetles captured, it could not differentiate among their species. However, as the rate of beetles captured outside the target species was not at a level that would affect the performance of the trap and the purpose of the study and the intervals of catching other species were not known, all records were used in the analysis. Although the number of beetles counted manually was 1622 with the number of beetles recorded by ECU pheromone trap was 1692. There was no statistically significant difference between the number of beetles captured according to these two different counting methods ($p > 0.05$; Table 2).

When the beetle numbers determined using these two counting methods were compared, the ECU pheromone trap counted with an error rate of 4%, in other words, with an accuracy of 96%. As it could be seen in Table 2, this ratio Is neglected as there was no statistically significant difference and ECU pheromone trap records were considered in evaluations.

During the study, a daily average of a total 16.4 ± 17.2 *I. sexdentatus* was captured in the trap. Of the total beetles, 59% was captured between May

Table 2 Comparison of different counting methods with Mann–Whitney *U* test

Counting methods	N	Mean rank	Sum of ranks	P
Manual	103	101.77	10,482.00	0.676
ECU pheromone trap	103	105.23	10,839.00	

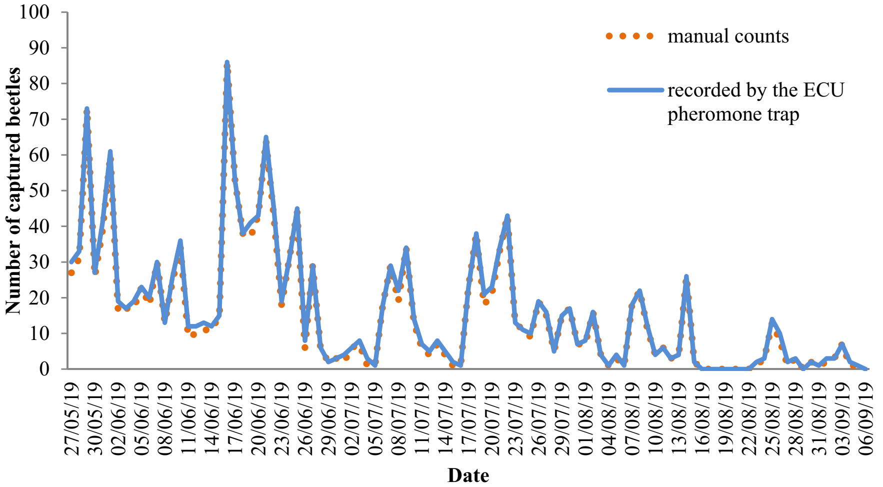

Fig. 2 Distribution of beetles recorded by pheromone trap and counted manually according to days

27 and June 25 (30 days), and the highest catch was on June 16 with 86 beetles. The average number of beetles captured in the trap in this time interval is 33.2 ± 19.3, approximately twice the average number of beetle in the entire study. It is estimated that the target species had its spring flight during this 1-month period. The captures significantly decreased after August 15 (Fig. 2).

In 24% (594) of the total data range of 2472 units, *I. sexdentatus* was captured in the trap, whereas in 76% (1878), they were not. The average temperature was 18.7 °C, average humidity 68%, and average wind speed 2.4 m/s for all days during the study (Table 3). The parameters recorded by the ECU pheromone trap with the interpolated data of the meteorological station are compatible. Therefore, ECU pheromone trap recordings were used in the analysis.

Considering the 594 units of data in which *I. sexdentatus* was captured, it was determined that the average temperature, humidity, and wind speed were 20.09 °C, 66%, and 2.9 m/s, respectively. There were statistically significant differences among the average temperature, humidity, and wind speed in the data intervals at the time of capture and non-capture ($p < 0,05$; Table 4).

There was a statistically significant difference in terms of capture of *I. sexdentatus* according to five different temperature groups ($p < 0.05$), and there is a relationship between temperature values and beetle capture (Table 5). Besides, the highest captures were in the ranges of 15–19.99 °C (227) and 20–24.99 °C (212) temperature ranges. More specifically, 73.9% of the captures occurred at a temperature range of 15–24.99 °C. The target species was captured with the lowest temperature of 10.32 °C at 19:52:54 on June 30 and at the highest temperature of 31.12 °C at 09:55:23 on July 15.

There is a statistically significant difference in terms of capture of *I. sexdentatus* and humidity ($p < 0,05$), and humidity affects the catching of beetles (Table 6). In addition, the highest captures were in the ranges of 61–70% (104), 71–80% (113), and 81–90% (146) humidity. In other terms, 61.1% of the captures occurred in the 61–90% humidity range. *I. sexdentatus* was captured at the lowest humidity of 23% at 11:08:56 on August 8 and the highest humidity of 93% at 16:28:45 on June 12.

A statistically significant difference was observed between the number of captured *I. sexdentatus* and the measured wind speeds ($p < 0.05$), with a correlation between wind speed and capturing of the beetles (Table 7). The highest captures occurred in the wind speed ranges of 0.3–1.5 m/s (127), 1.6–3.3 m/s (274), and 3.4–5.4 m/s (131). The highest capture was observed in the 0.3–5.4 m/s wind speed range, with

Table 3 Temperature, humidity, and wind speed parameters for the study period

Parameter	N	Minimum	Maximum	Average ± SD
Temperature (°C)	2472	7.2	37.1	18.7 ± 5.033
Humidity (%)	2472	20	96	68 ± 0.173
Wind speed (m/s)	2472	0	9.4	2.4 ± 1.645

Table 4 Mann–Whitney *U* test, comparison of temperature, humidity, and wind speed parameters of *Ips sexdentatus* at the time of capture and non-capture

Parameter	Capture status	N	Min	Max	Average ± SD	Mean rank	Sum of ranks	P
Temperature (°C)	Present	594	10.3	31.1	20.1 ± 4.2	1458.41	866,297.50	< 0,001
	Absent	1878	7.4	37.1	18.3 ± 5.2	1166.31	2,190,330.50	
Humidity (%)	Present	594	23	93	66 ± 0.2	1126.56	669,175.50	< 0,001
	Absent	1878	20	96	69.1 ± 0.2	1271.27	2,387,452.50	
Wind speed (m/s)	Present	594	20	9.4	2.9 ± 1.7	1459.88	867,171.50	< 0,001
	Absent	1878	0	9.1	2.3 ± 1.6	1165.84	2,189,456.50	

89.6% of the captures occurred at the wind speed in this range. *I. sexdentatus* was captured at the lowest wind speed of 0 m/s on July 6 at 18:49:53 and the highest wind speed of 9.4 m/s on July 10 at 13:02:15.

A statistically significant difference was observed in *I. sexdentatus* captures depending on the daylight time intervals ($p < 0.05$), with a correlation between daylight and capturing of the beetles (Table 8). The highest captures occurred from solar noon to sunset (269) and then the second from sunrise to solar noon (190). In other words, the highest number of captures occurred during the period from sunrise to sunset with 77.3% of the captures occurring in this range. Although daylight had a significant effect on capture, it has been observed that some captures also occurred at dark.

Captures of *I. sexdentatus* in ECU pheromone trap were affected by daylight, temperature, humidity, and wind speed. The Phi values were calculated to determine the strength of the relationship between these parameters and capturing of the beetles. According to the Phi (φ) values, the most to least strongly related parameters were as follows: daylight, temperature, wind speed, and humidity ($\varphi_{Daylight} = 0.239$; $\varphi_{Temperature} = 0.202$; $\varphi_{Wind\ speed} = 0.239$; $\varphi_{Humidity} = 0.119$; $p < 0.05$). In addition to the relations between these parameters and the status of *I. sexdentatus* being captured separately, an evaluation of the interrelations of all parameters was attempted. Therefore, a crosstab table was used for entering the key parameters related to the capturing in the order of the strength of the relation (daylight, temperature, wind speed, and humidity), and the intersections where the highest captures occurred were determined.

Accordingly, both in the time interval from noon to sunset and sunset to sunrise, the maximum number of captures is 1.6–3.3 m/s, in the temperature range of 15–19.99 °C occurred at wind speed and

Table 5 Distribution of captured *Ips sexdentatus* on temperature groups and Chi-square (X^2) test results

Parameter	Groups		Unit range		Total		Chi-square (X^2)	P
			Capture	Non-capture	N	%		
Temperature (°C)	7.42–14.99	N	68	589	657	26	100.414	< 0,001
		%	10.4	89.6	100			
	15–19.99	N	227	617	844	34.1		
		%	26.9	73.1	100			
	20–24.99	N	212	436	648	26.2		
		%	32.7	67.3	100			
	25–29.99	N	83	218	301	12.2		
		%	27.6	72.4	100			
	30–37.1	N	4	18	22	0.9		
		%	18.2	81.8	100			
Total		N	594	1878	2472	100		
		%	24	76	100			

Table 6 Distribution of captured *Ips sexdentatus* on humidity groups and Chi-square (X^2) test results

Parameter	Groups		Unit range		Total		Chi-square (X^2)	P
			Capture	Non-capture	N	%		
Humidity (%)	20–30	N	10	34	44	1	35.039	< 0,001
		%	22.7	77.3	100			
	31–40	N	35	115	150	6.1		
		%	23.3	76.7	100			
	41–50	N	69	136	205	8.3		
		%	33.7	66.3	100			
	51–60	N	96	252	348	14.1		
		%	27.6	72.4	100			
	61–70	N	104	310	414	16.7		
		%	25.1	74.9	100			
	71–80	N	113	386	499	20.2		
		%	22.6	77.4	100			
	81–90	N	146	461	607	24.6		
		%	24.1	75.9	100			
	91–93	N	21	184	205	8.3		
		%	10.2	89.8	100			
Total		N	594	1878	2472	100		
		%	24	76	100			

humidity range of 81–90%. Within the time interval from sunrise to solar noon, the most number of captures occurred in the temperature range of 20–24.99 °C, wind speed of 1.6–3.3 m/s, and humidity of 51–60% and 61–70%.

Discussion

Although the flight periods of bark beetles vary from year to year (Panzavolta et al., 2014), adults fly in search of host trees for new breeding sites

Table 7 Distribution of captured *Ips sexdentatus* on humidity groups and Chi-square (X^2) test results

Parameter	Groups		Unit range		Total		Chi-square (X^2)	P
			Capture	Non-capture	N	%		
Wind speed (m/s)	0–0.2	N	1	20	21	0.8	71.218	< 0,001
		%	4.8	95.2	100			
	0.3–1.5	N	127	702	829	33.5		
		%	15.3	84.7	100			
	1.6–3.3	N	274	772	1,046	42.3		
		%	26.2	73.8	100			
	3.4–5.4	N	131	264	395	16		
		%	33.2	66.8	100			
	5.5–7.9	N	56	116	172	7		
		%	32.6	67.4	100			
	8.0–10.7	N	5	4	9	0.4		
		%	55.6	44.4	100			
Total		N	594	1878	2472	100		
		%	24	76	100			

Table 8 Distribution of captured *Ips sexdentatus* on daylight groups and Chi-square (X^2) test results

Parameter	Groups		Unit range		Total		Chi-square (X^2)	P
			Capture	Non-capture	N	%		
Daylight	Sunset–sunrise	N	135	840	975	39.5	141.101	< 0,001
		%	13.8	86.2	100			
	Sunrise–solar noon	N	190	619	809	32.7		
		%	23.5	76.5	100			
	Solar noon–sunset	N	269	419	688	27.8		
		%	39.1	60.9	100			
Total		N	594	1878	2472	100		
		%	24	760	100			

(Jones et al., 2019). There are two flight periods for *I. sexdentatus* in forests in Turkey: the first is between April and May, and the latter is between June and July (Yüksel et al., 2000). In the Crimean pine forests of the region where this study was conducted, the target species was observed to have two flight peaks, one in May and the other in September (Özcan, 2017). The ECU pheromone trap was left in the field between late May and early September. This period is within the local flight periods of *I. sexdentatus* in the regional forests and includes the times when the most captures generally occur.

Overall, 59% of the total beetles were captured during the spring flight period between May and the end of June, and the daily average of beetles captured in this period was approximately two times higher when compared with the rest of the study period. Similarly, Özcan (2017) reported, in the same region, that 69% of the total beetles were captured in the traps within the same period, mostly in May, and accordingly, spring captures were much higher than summer captures. Also, the highest captures occurred during the spring flight in spruce forests (Özcan et al., 2011). Similarly, spring captures of *I. typographus* are always higher than summer captures (Faccoli & Buffo, 2004). For the present study, literature data has been taken into account for this particular region so that the ECU pheromone trap could be placed in the correct time interval.

Overall, 1.7% of the beetles captured in the trap were *T. formicarius*. *T. formicarius* is a generalist predator (Tommeras, 1988; Warzee & Gregoire, 2003) of at least 20 bark beetle species (Seedre, 2005), and it plays a crucial role in suppressing harmful species (Schroeder, 2001; Schroeder & Weslien, 1994; Weslien, 1992). In addition, the predator is attracted to bark beetle pheromones (Schroeder, 1997), and it reacts to the same pheromones as their prey (Aukema et al., 2000). Özcan et al. (2011) reported that the predator was captured even if no bark beetle species was captured in pheromone traps. As the biological control carried out by this predator is effective in reducing pest populations (Eneh, 2011), the predators collected from the trap chambers during the study were released back to the forest. Although other beetles in forest areas are likely to be captured in traps (Majumdar & Reed, 2013), their number was lower than the target species. The chamber entrance of the used ECU pheromone trap is designed narrower than the traditionally used traps. In this manner, under natural conditions, although entering the trap is easy for the target species, it is difficult for the predators and larger beetles. Therefore, this feature of the trap has been experimented with this study, and it resulted as an advantage of the designed trap.

When the number of beetles recorded by the ECU pheromone trap and that counted manually was compared, the designed trap was determined to work with an error margin of 4%, indicating a success rate of 96%. This error rate might have been due to the movements of some beetles captured in the trap just before they fall into the trap chamber, causing detection on the sensor. In the first design of this trap, the success rate of this trap was between 86.7 and 90.2% in the workshop trials performed by throwing the dead adults of *I. sexdentatus* manually at different time intervals and numbers (Özcan et al., 2016). The success rate of the renewed and redesigned ECU pheromone trap used in this study was 97–98.1% in workshop trials conducted with the same target species (Özcan et al., 2018).

In this study, the success rate achieved in the field, considering the movements of captured beetles, was quite high. Trap designs with automatic detection techniques and with efficiencies of 90–96% (Rustia et al., 2020), > 80% (Xia et al., 2015), > 97% (Ebrahimi et al., 2017), 85–95% (Lu et al., 2019), and 96% (Huddar et al., 2012) have been recently developed for agricultural pests. These approaches provide an innovative approach to integrated pest management (Lima et al., 2020). This study can help achieve integration in the field of forestry. During the time intervals when *I. sexdentatus* was trapped, the average temperature was 20.09 °C, average humidity was 66%, and average wind speed was 2.9 m/s. The spring flight of the species begins when the temperature rises above 20 °C: this flight occurs in May–June in the northern regions and March–April in the southern regions (Vité et al., 1974). In this study, since air temperatures were already > 20 °C when trapping commenced, it is likely that the target species started its initial flight before that. However, statistically significant differences were found among the average temperature, humidity, and wind speed between the times of capture and non-capture. These parameters appear to affect the beetles' flight and, accordingly, its capture in the pheromone trap.

The temperature which affects the behavior, spread, development, and reproduction of bark beetles is one of the most important abiotic factors affecting the flight of beetles (Bale et al., 2002; Şimşek et al., 2010). In addition to temperature, daylight intensity, wind speed, precipitation, and relative humidity affect the flight activity of beetles (Haack, 1985; Östrand & Anderbrant, 2003; Pawson et al., 2017). However, trials with *Ips grandicollis* (Eichhoff) report that humidity does not affect the response of the beetles to pheromones, except under unexpected conditions such as excessive humidity (Bassett et al., 2011). The distribution of bark beetles may occur in short distances in a stand or in forests at longer distances due to the effect of wind (Jones et al., 2019). After maturity, the beetles fly in the direction of the wind until they encounter attractive signals, and then, they head for the signal responding to it (Gray et al., 1972; Safranyik et al., 1992). Just as the time of day and temperature at that hour trigger flight activity (Pawson et al., 2017), daily temperatures also affect the rate at which beetles are captured in traps (Bakke, 1992). Moreover, microclimatic conditions play an important role in flight activity (Annila, 1969). The study evaluations showed that 73.9% of the captures occurred at a temperature range of 15–24.9 °C, 61.1% at humidity of 61–90%, 89.6% at wind speed of 0.3–5.4 m/s, and 77.3% within the period from sunrise to sunset. These four factors affect the capturing of the beetles, and when these are evaluated together, the most effective is daylight, followed by temperature, wind speed, and humidity. The times when these conditions are experienced represent the periods when *I. sexdentatus* is most active in searching suitable host trees. Hence, it is important to be more careful when these conditions are being experienced, to increase the monitoring, and to take precautions to reduce possible forest damage.

I. sexdentatus was captured at the lowest temperature of 10.3 °C on June 30 and the highest temperature of 31.1 °C on July 15. Although it has not been possible to determine data for the beginning of the flight of the beetle in this study, it was stated in the study by Ozcan (2017) that the average daily temperature was approximately 11 °C on the days when the first flying of the target species started. When beetles begin to fly, they can continue to fly even at temperatures below the optimum levels (Atkins, 1961; Gaylord et al., 2008). Gaylord et al. (2008) reported in the study conducted with pheromone traps that the *Ips pini* (Say) can perform its initial flight at 16.1 °C minimum 11.7 °C (March) and maximum > 41 °C, but the optimal temperature for flight is 17–38.9 °C. It is reported that *Ips lecontei* Swaine can perform its initial flight at 19 °C minimum 15.2 °C (March) and maximum temperature > 41 °C, but the optimal temperature for flight is 19–38.9 °C. It is stated that *Ips calligraphus* (Germar) can perform its initial flight at 18.6 °C minimum 15.5 °C (October) and flies at maximum temperature > 41 °C, but the optimal temperature for flight is 20–38.9 °C. At the same time, *Ips typographus* (L.) can perform its initial flight at 16 °C minimum 17.5 °C (Botterweg, 1982; Öhrn et al., 2014; Wermelinger, 2004). A study evaluating the flight of *Pityophthorus juglandis* Blackman per day has stated that it makes its maximum flight at 11–27 °C (Chen & Seybold, 2014). Compared to other *Ips* species, *I. sexdentatus* can fly at a minimum 10,3 °C and a maximum temperature 31,1 °C. Also, it is the optimal temperature for flight which is 15–24.9 °C. The present study determined that *I. sexdentatus* flies at lower temperatures than other species and performs its optimum flight in the lower temperature range.

Although daylight significantly affected trapping of beetles, they are also captured when there is no daylight. *Dendroctonus ponderosae* Hopkins is reported to have a very limited and negligible flight in the dark (Wijerathna, 2016); the flight distance of *Dendroctonus armandi* Tsai and Li is affected by the quality of light; the flight is mostly in the morning and afternoon hours and decreases in the dark (Chen et al., 2010). *Xylosandrus germanus* (Blandford) prefers low light intensities for flight but does not fly in the dark (Weber, 1982), and the most effective environmental factor in flight activity in *I. typographus* is the light intensity; more beetles fly on sunny days (Wermelinger, 2004). Daylight had a significant effect on capture for *I. sexdentatus*, but it has been found out that low rate captures occurred at dark.

Conclusion

Information related to the quantitative evaluation of factors affecting the flight of bark beetles and the conditions of their capture by pheromone traps is important for understanding ecological processes. Using trap data for target species according to parameters in field conditions will facilitate the achievement of precision forestry aims. Determining the temperature, humidity, wind speed, and daylight requirements for economically important bark beetles in forestry will provide an integrated approach to guide pest control management. This approach will also help determine the timing of the potential pest management strategy. The new generation trap has some important advantages such as less time consuming, less labor, less expense, and detailed data. The results of this study will contribute toward reducing forest damage, damage severity, and economic losses in line with sustainable forestry policies.

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Author contribution GEO participated in the designing of the study, carried out field study, collected the data, analyzed the data, and write the manuscript. HŞT carried out field study and helped to draft the manuscript. All authors read and approved the final manuscript.

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