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Development of an electrostatic trap with an insect discharge recorder for multiple real-time monitoring of pests prowling in a warehouse

Takikawa Y.[1], Matsuda Y.[2]*, Nonomura T.[2], Kakutani K.[3], Kusakari S.[2] and Toyoda H.[2]

[1]Plant Center, Institute of Advanced Technology, Kinki University, Wakayama 642-0017, Japan.
[2]Laboratory of Phytoprotection Science and Technology, Faculty of Agriculture, Kinki University, Nara 631-8505, Japan.
[3]Pharmaceutical Research and Technology Institute, Kinki University, Osaka 577-8502, Japan.

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ABSTRACT

Reliable information of pests dwelling in a warehouse is a prerequisite to construct an effective and realistic pest control strategy. Our new electrostatic pest-monitoring apparatus is presented for this purpose. The apparatus consists of an insect-discharge detector and electrostatic insect trap. The detector is an iron plate attached to a direct current (DC) positive voltage generator and the insect trap consists of a pair of opposite poles. Pests on the detector plate are stripped of free electrons and charged positively. This is recorded as a transient discharge signal from the insect, and the positively charged pests are trapped at the negative pole. Discharge signals from different checkpoints in a warehouse were monitored automatically and continuously to analyze the temporal and spatial movements of the pests. This monitoring system enabled us to apply most effective chemical and physical methods to the control of cigarette beetles dwelling in our warehouse.

INTRODUCTION

Effective pest management in the storage of harvested agricultural crops and their products is important for supplying safe food materials. Some chemical (Hill, 1990) and physical measures (Matsuda et al., 2011) have been applied in the control of warehouse pests. Adult cigarette beetles damage a wide range of stored agricultural products, including cocoa, beans, cereals, cereal products, oilseeds, pulses, spices, dried fruits, cured tobacco leaves, and some animal products. Both larva and adult red flour beetles damage dry food materials, such as ground rice, wheat flour, cornmeal, spices, cottonseed flour, and livestock foods. Adult rice weevils cause serious damage to rice grains in addition to several cereal grains and beans. These pests can multiply rapidly in storage bags and spoil postharvest crops, and in postharvest crop protection, these insects have been targeted as the most serious pests (Hill, 1990).

To determine the most reliable approach for pest control in warehouses, identifying targeted pests rapidly and assessing their temporal and spatial movements precisely is essential. Consequently, we sought to develop an efficient method to detect specific electric signals from pests to track their movements. This idea was based on findings that the insect cuticle layer (the outer protective layer covering the body of many invertebrates) is highly conductive (Ishay et al., 1992; McGonigle and Jackson, 2002; McGonigle et al., 2002; Honna et al., 2008; Moussian, 2010) and that free electrons in this layer are affected by an electric field (Kakutani et al., 2012a; b; Nonomura et al., 2014).

Here, we propose a new electrostatic system for monitoring the insect pests prowling in a warehouse. The system consists of a unique insect-discharge detector,

*Corresponding author. E-mail: ymatsuda@nara.kindai.ac.jp.
Tel: +81-742-435223.

which is placed in a flat box with a narrow tunnel, the floor of which is a grounded iron conductor plate. Our experimental design exploited the habitual behavior of insects to enter narrow gaps (Burkholder, 1984; Klotz and Reid, 1992) and strips the free electrons from the insect cuticle by positively charging the conductor plate on the tunnel floor. These electrons move to the ground and are detectable as a current using a galvanometer integrated in the earth line. The monitoring system can collect insect-specific signals continuously from discharge recorders set at multiple points in a warehouse. In addition to signal recognition, the correct identification of the pests is needed to determine the best way to eradicate them. As capturing pests is the most direct way to identify them, we attached an electrostatic trap to the discharge-detection box to catch insects passing over the discharge-detection plate. This trap is a simple modified version (two insulated conductor wires paired with an earthed metal plate) of the electrostatic insect-capturing instrument reported by Kakutani et al. (2012a).

MATERIALS AND METHODS

Test insects

Adult cigarette beetles (*Lasioderma serricorne*) were obtained from stock cultures maintained for several years in the laboratory of the Leaf Tobacco Research Center (Tochigi, Japan) (Hori and Kasaishi, 2005). The cigarette beetles were reared on oatmeal powder in plastic containers (20 cm in diameter, 10 cm high) at 25 ± 2°C and 60 ± 5% relative humidity (RH) in the laboratory at Kinki University (Higashiosaka, Japan). Larvae of the red flour beetle (*Tribolium castaneum*) and rice weevil (*Sitophilus oryzae*) were purchased from SumikaTechnoservice (Hyogo, Japan) and incubated to eclosion in a growth chamber under the above conditions. Adult test insects were collected using an insect aspirator (Wildlife Supply, NY, USA). The width of the insect body was measured in 30 adult insects collected randomly to determine whether they could pass through conventional woven insect nets (mesh size, 1.5 –1.6 mm) having widths of 1.21 ± 0.11, 1.19 ± 0.09, and 1.23 ± 0.08 mm for the cigarette beetle, red flour beetle, and rice weevil, respectively.

Experimental equipment

The pest - monitoring apparatus consists of two electrostatic instruments: The insect-discharge detector and electrostatic insect trap. Both instruments were placed inside elongated rectangular boxes measuring 25 cm wide, 3 cm long, and 0.4 cm high, with an interior 0.2 cm- high tunnel allowing insect passage.

Insect-discharge detector

The signal-generating part of the insect-discharge detector (black polypropylene) was an iron plate on the tunnel floor (Figure 1A). The plate was linked to a direct current(DC) positive voltage generator (DMS-PBX, Max-Electronics, Tokyo, Japan) and positively charged with 1.0–10.0 kV. Test insects were released onto the charged plate and the transfer of free electrons from the insect cuticle to ground was measured with a galvanometer (LR8511, Hioki, Nagano, Japan) integrated in the earth line of the voltage generator. The charge transfer was recorded as an electric current with a recorder built into the galvanometer. Twenty insects were used for each voltage, and the mean values of the highest magnitudes of electric current instantaneously discharged from the insect were plotted with the standard deviations. Regression lines were calculated to estimate the maximum amount of dischargeable electricity from an insect.

Electrostatic insect trap box

To construct the insect trap inside the box made of transparent acrylic, an earthed iron plate was installed on the tunnel floor, and two insulated conductors connected both ends of the tunnel ceiling (Figure 1B). The insulated conductor was prepared by passing a 2mm-diameter, 25cm-long iron wire through a transparent insulator vinyl sleeve (1 mm thickness, $1 \times 10^9 \Omega$). The two insulated conductors were connected to each other and a DC negative voltage generator (BMS-NBX, Max-Electronics); and were negatively charged with 1.0–10.0 kV. The negative surface charges of the insulated conductors polarized the earthed plate on the floor, creating a positive charge on the surface of the plate (Kakutani et al., 2012a); the opposite charges acted as dipoles that formed an electric field between the insulated conductors and earthed plate. Test insects were released onto the earthed plate to examine the ability of the insulated conductors to attract insects, which was recorded with a digital EOS camera (Canon, Tokyo, Japan) (Figure 1B).

To confirm the successful capture of test insects with the insulated conductors, we directed a blower (max. wind speed 7 m/s at the wire) at the captured insects for 10 min. Seven to 10 adults were used for each species and for each voltage tested. Experiments were repeated five times, and the data are presented as means ± SD. Significant differences among the data were analyzed using Tukey’s method (see legend to Table 1). All voltage generators used in this study were operated using 12V storage batteries. Here, we optimized the voltage conditions for positively electrifying the discharge detector plate in the discharge detector box and negatively electrifying the insulated conductor wires in the

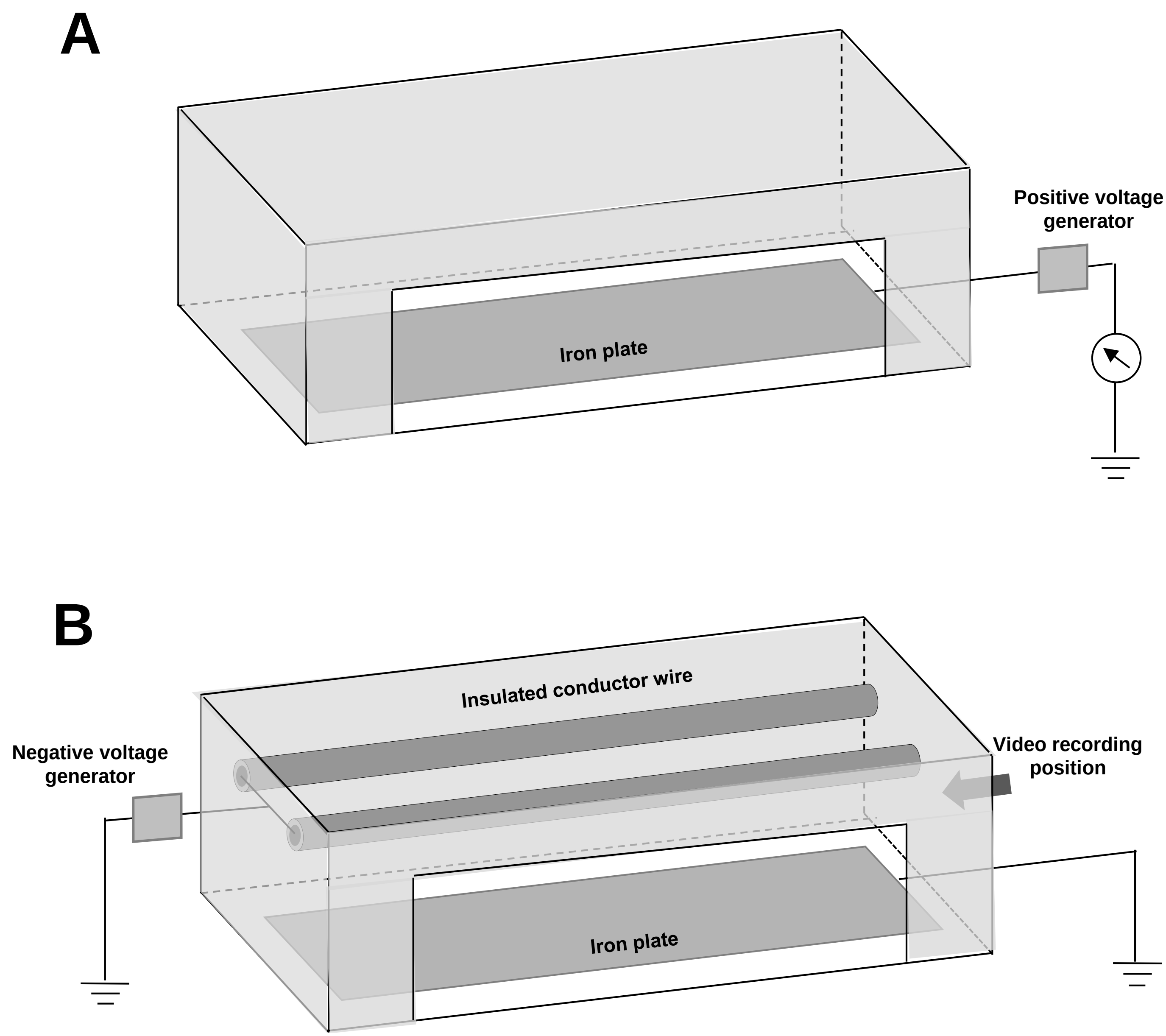

Figure1. Diagram of the insect discharge detector (A) and electrostatic insect trap (B) in a box. The iron plate in the discharge detector was linked to a DC positive voltage generator, and a galvanometer was integrated in the earthed line of the voltage generator to measure the direction and magnitude of the bioelectric current.

Table 1. Percentage of insects captured by insulated conductor wires of an electrostatic trap.

Insect pests tested	Negative voltages (kV) applied to insulated conductor wires									
	0.5	**1**	**15**	**2**	**2.5**	**3**	**3.5**	**4**	**6**	**8.5**
Cigarette beetle	0	0	0	24.0±8.4 a	89.0±5.4 a	100 a	100	100	100	100
Red flour beetle	0	0	0	0 b	18.0±6.0 b	82.0±8.7 b	100	100	100	100
Rice weevil	0	0	0	26.0±9.2 a	91.0±9.4 a	100 a	100	100	100	100

Seven to ten adults were used for each insect species, and the means and standard deviations were calculated from five replicates. The different letters (a and b) on the mean values on each vertical column indicate significant differences (p<0.5) according to Tukey's method.

trap box using three common warehouse pests: The cigarette beetle (*L. serricorne*), red flour beetle (*T. castaneum*), and rice weevil (*S. oryzae*).

Monitoring and subsequent control of warehouse pests

A monitoring experiment was conducted using a pest-monitoring unit. The unit consisted of two discharge detectors and the insect trap (Figure 2A). The boxes could all be connected to each other so that the passage floors were flat and continuous. The practicability of the current-monitoring system was tested in an air-conditioned warehouse (with two exhaust ports, two air ports, and two small windows covered with conventionally woven insect nets with 1.5 mm mesh) containing bags of commercial dry-powdered diet for rats and rabbits. Six pest-monitoring units were placed at several locations in the warehouse, near each exhaust port, air port, and window, and some opened bags were placed in the center of the warehouse to attract pests. All insect discharge data recorded in the galvanometers were transferred wirelessly to a radio receiver (LR8410 Wireless Logging Station, Hioki, Nagano, Japan) attached to a central computer for analyzing the movements of the pests. The data were charted automatically for 7 days using data-analysis software (PC Link 7, Sanwa, Tokyo, Japan) (Figure 2B). At the end of the monitoring period, the pests captured with the insulated conductors in the insect traps were counted and collected for identification.

Pest control was performed using chemical extermination of pests living in the warehouse facilities and physical repellence of pests entering via the window. The exhaust ports and air ports were fumigated with phosphine (a colorless, foul-smelling gaseous pesticide consisting of phosphorous and hydrogen) to kill the pests living inside using a previously reported method (Hori and Kasaishi, 2005). External pests were prevented from entering the warehouse by installing electric field screens on the window, instead of the woven insect nets, as described previously (Matsuda et al., 2011); the screen consisted of insulated conductors arranged in parallel and two earthed conductor nets (mesh size 1.5 mm) placed on both sides of the wires, and it was able to repel pests reaching the screen net. The effectiveness of the pest control treatments was evaluated by checking the pest traps and food bags for pests.

RESULTS AND DISCUSSION

Detection of the insect discharge signal

The work focused on evaluating electrical signals from pests at various locations in the warehouse. The first experiment investigated whether an insect discharge could be induced using the electrostatic equipment and then whether this discharge could be used as a signal for tracing prowling pests. Figure 3 shows the relationship between the electric current generated and the applied voltage in cigarette beetles (A), red flour beetles (B), and rice weevils (C). For all three species, an electric current was first detected at 5.0 kV and was directly proportional to the increase in the voltage over the range of 5.0–8.2 kV. At higher voltages, no increase was observed in the electric current, that is, these values corresponded to the upper limit of the transmittable electricity of the insects. In all cases, the electric current was generated immediately and transiently after the insects were released on the discharge - detector plate. An electric current was generated just once, even when the insects remained in place or walked along the plate, which is vital when evaluating the effectiveness of the method because the number of pests can be determined by counting the number of discharge signals. Judging from these results, we concluded that the electric current-counting method was acceptable, which strongly supports our previous supposition that the highly conductive insect cuticle is the original site of electric current generation (Kakutani et al., 2012a, b). From these results, we charged the discharge-detector plate at 8.2 kV in the following experiments.

An additional advantage of the apparatus was that the discharge-detector plate was set on the floor of a narrow tunnel inside the box. This tunnel led the pests to the discharge-detector plate because many warehouse pests have an intrinsic habit of entering narrow gaps (Burkholder, 1984; Klotz and Reid, 1992). The test insects behaved similarly in our preliminary survey. In fact, all three test insect species released in the warehouse promptly entered the discharge detectors placed in several corners of the room, and the wide frontage of the tunnel was useful for promoting pest entry (data not shown).

Electrostatic trapping of insects

Before conducting the insect - trapping assay, we examined the discharge from the insulated conductor at different voltages. For this purpose, a galvanometer was integrated in the earthed line of the iron floor plate in the electrostatic insect trap. An electric current from the insulated conductor to the ground was detected at >8.6 kV. At 8.6–10.0 kV, the current magnitude rose from 0.01 to 0.12 μA as the voltage increased. The current magnitude was continuous and constant at each voltage. In the following experiments, the insect - trapping experiment was performed at voltages <8.6 kV to avoid causing needless discharge from the insulated conductors.

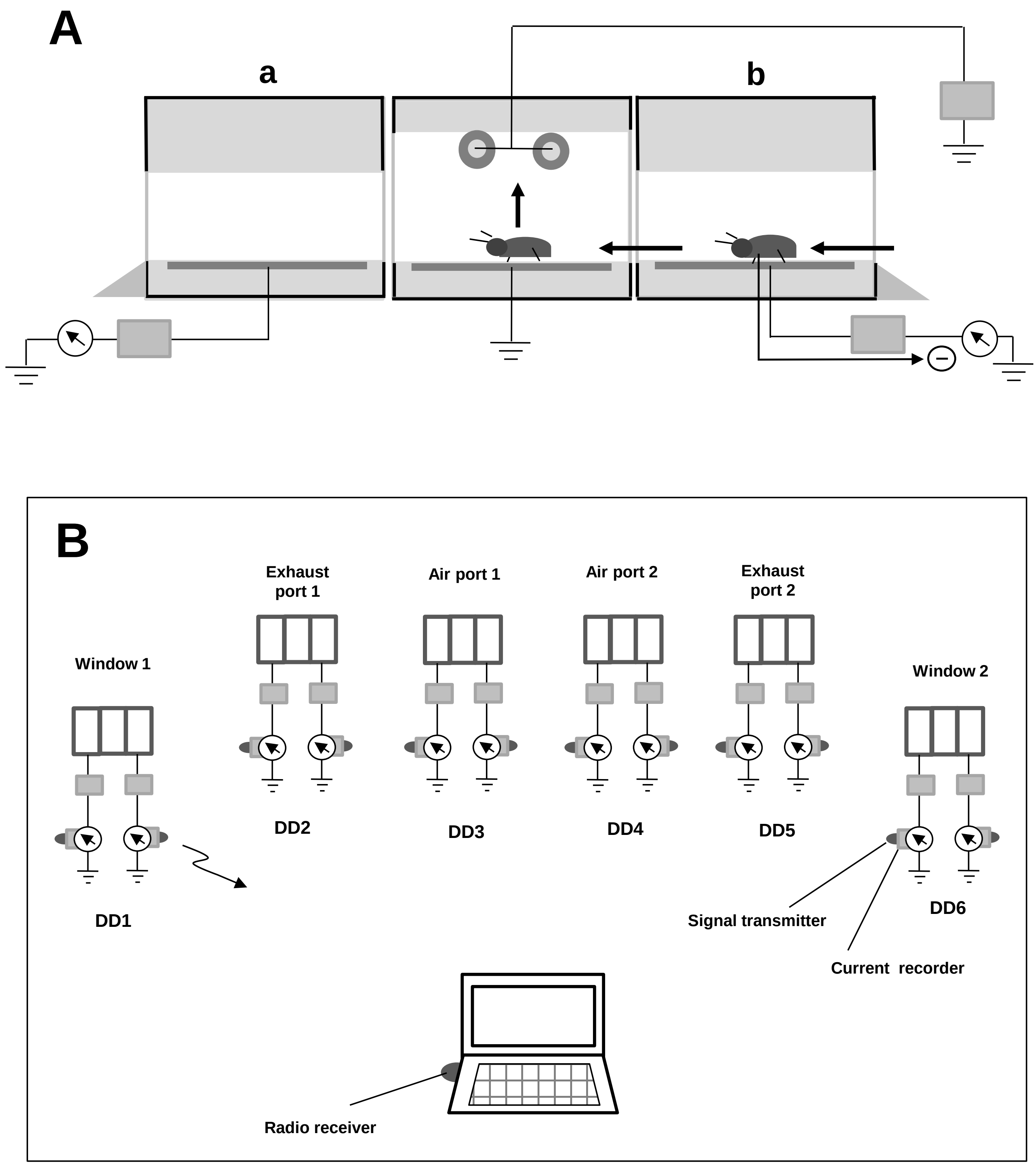

Figure 2. Electrostatic pest monitoring system. (A) The pest-monitoring box consisted of two insect-discharge detectors (a and b) and an electrostatic insect trap. Bold arrows show the direction of insect movement or attraction and the fine arrow indicates the direction of transfer of the insect charge. (B) Central control system for the insect discharge signals transmitted wirelessly from the multiple monitoring boxes set at different points. Six pest-monitoring boxes (DD1 to DD6) were set near two windows, two exhaust ports, and two air ports. Using a signal transmitter attached to the current recorder of a galvanometer, the insect discharge signals in each box were transmitted wirelessly to a radio receiver and a central computer.

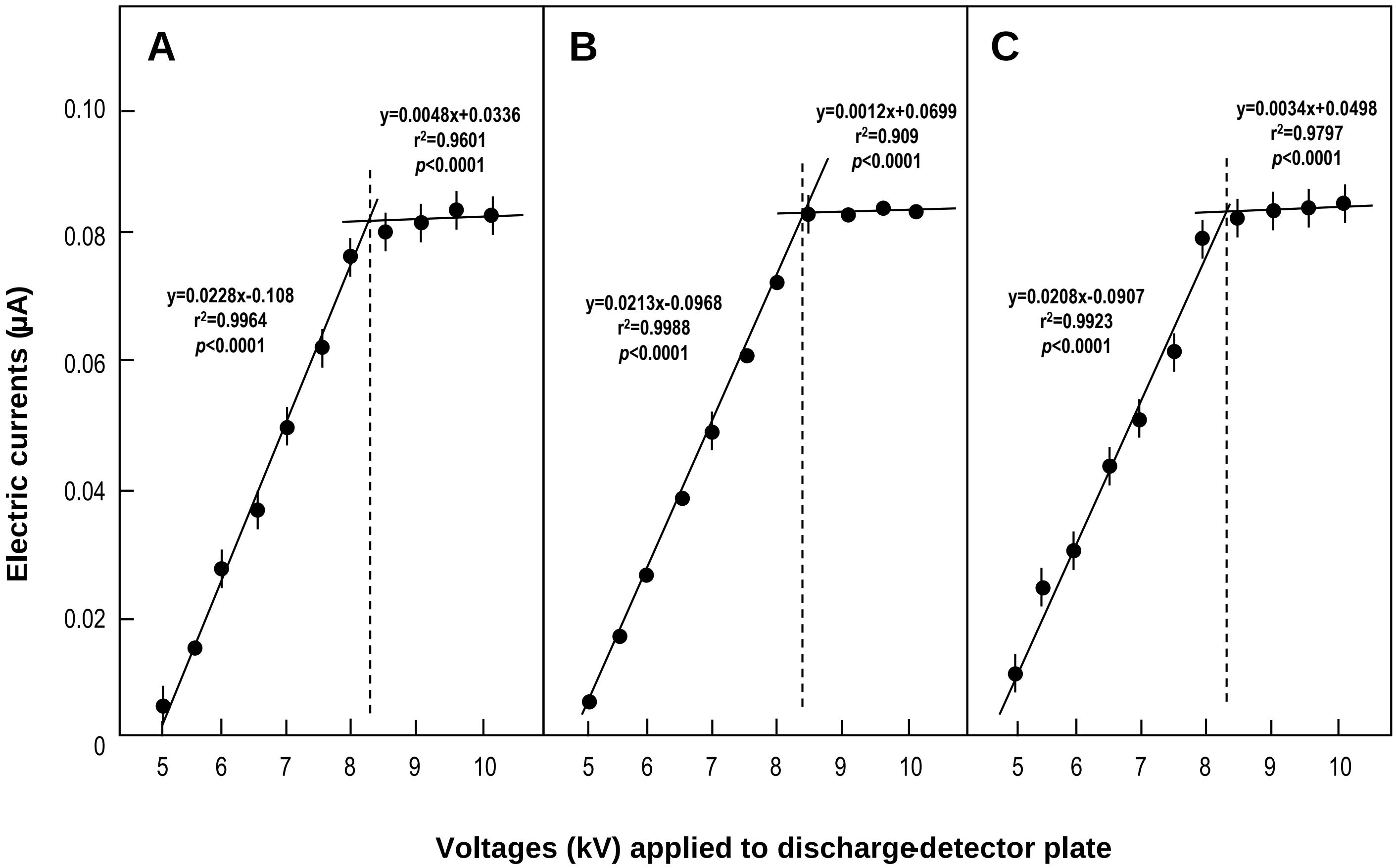

Figure 3. Electricity discharged from adult cigarette beetles (A), red flour beetles (B), and rice weevils (C) on the positively charged iron plate in the discharge detector. Twenty insects were used for each voltage, and the mean magnitude of the electric current instantaneously discharged from the insect was plotted with the standard deviation. Two regression lines are plotted, and the maximum amount of dischargeable electricity of the insect was estimated from the intercept (dotted line) of the two lines.

Our observation of the insects in the pest-monitoring unit revealed that all insects reaching the discharge-detector plate moved into the trap box without returning. Occasionally, some insects stopped or walked sideways on the plate, but they ultimately entered the next box.

As previously noted, the insects at this stage were positively charged as the result of electron stripping. In our strategy, these positively charged insects are readily attracted by the negative charge of the insulated conductors in the insect trap box. The mechanism for capturing insects with insulated conductors was described previously (Kakutani et al., 2012a). Table 1 lists the percentage of test insects captured by the insulated conductors at different voltages (0.5–8.5 kV). The force increased with the voltage applied to the insulated conductors. No significant difference was observed in the capture rate among the three insect species (cigarette beetles, red flour beetles, and rice weevils). At >3.5 kV, the force was strong enough that the insulated conductors captured all adults, regardless of insect species. Video data showed the successful attraction of test insects (Video supplement available at: https://www.dropbox.com/s/vewfyirkl6jkym3/Video%20supplement%201.mp4?dl=0), and the force at the site was strong enough to capture insects despite a 7 m/s wind speed. These results indicated that an insulated conductor charged with >3.5 kV could deal with all major pest insects studied under real-world conditions in a warehouse. At lower voltages, however, the force was insufficient to capture the insects permanently; the captured cigarette beetles used their wings or legs to escape the insulated conductor or they were blown off it by the blower. Based on these observations, in the subsequent experiments, the insect trap was charged with 3.5 kV to ensure successful capture.

Monitoring-directed pest control

The practicability of our monitoring system was tested in

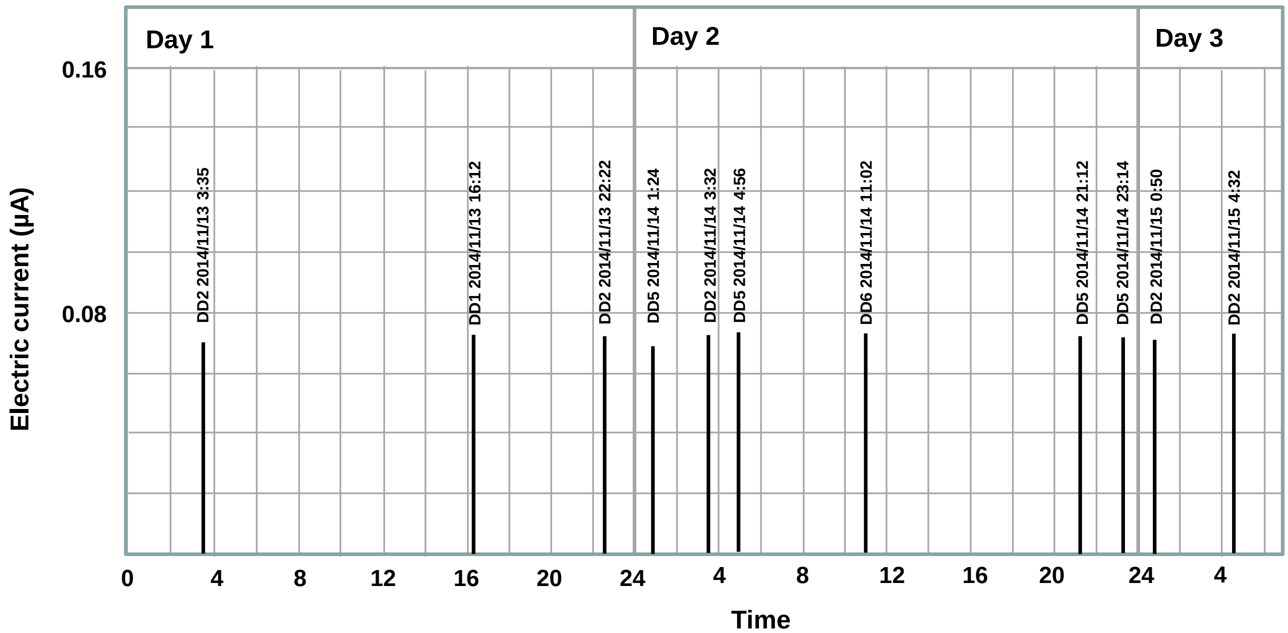

Figure 4. A chart of the automatically recorded electric current signals transmitted from multiple insect-discharge detectors during a 7-day period.

Table 2. Monitoring of warehouse pests by an electrostatic pest monitoring system and subsequent pest control results.

Pest monitoring box[a]	**Position of setting**	**Number of insect discharge signals before pest control treatment**			**Pest control treatment[c]**	**Number of insect discharge signals after pest control treatment**		
		1	**2**	**3[b]**		**1**	**2**	**3[b]**
DD 1	Window 1	2 (2)	0	3 (3[b])	EF-screen	0	0	0
DD 2	Exhaust port 1	12 (12)	10 (10)	16 (16)	Fumigation	0	0	0
DD 3	Air port 1	0	0	0	No treatment	0	0	0
DD 4	Air port 2	0	0	0	No treatment	0	0	0
DD 5	Exhaust port 2	9 (9)	14 (14)	13 (13)	Fumigation	0	0	0
DD 6	Window 2	1 (1)	4 (4)	0	EF-screen	0	0	0

[a]Refer to Figure 2B.
[b]Number of experiment. In each experiment the monitoring was continued for 7 days.
[c]Window were furnished with electric field screens (EF-screens) to prevent field pests from entering the warehouse and the exhaust ports were fumigated with phosphine to eradicate pests nesting in the ports.
[d]Number of pests trapped by the electrostatic trap attached to the discharge recorder box.

an air-conditioned warehouse containing bagged dry-powdered feed for rats and rabbits, as such feed is frequently and heavily infested with cigarette beetles. In our survey, all of the trapped pests were cigarette beetles. Accordingly, we sought to clarify the invasion routes of the cigarette beetles and to plan an efficacious strategy for devising a pest-free warehouse. Figure 4 shows a recording of the discharge signals collected from the pest-monitoring units placed at six points in the warehouse. The chart provides the origin of the signals and the time and date of signaling. The data are summarized in Table 2, which indicates that most of the discharge signals originated from the two units placed in front of the exhaust ports, while a few signals came from units near the windows. In addition, the signals were generated at night, indicating that the cigarette beetles prowled nocturnally, when no workers were in the warehouse. Similar results were obtained in repeated experiments. At the end of each experiment, we confirmed that the number of discharge signals from each unit equaled the number of pests captured by the trap in the same unit. These results indicate that the majority of the pests were cigarette beetles entering through the warehouse exhaust ports. In fact, the ports appeared to be suitable for cigarette beetle nests because the port floor was thinly covered with food powder transmitted by the exhausted air, and this fed the pests nesting in the exhaust ports. Table 2 also shows that the windows were an additional gateway through which pests invaded the warehouse, although the frequency of entry was low and occasional. The current-monitoring approach located the route of pest invasion and provided basic information for planning appropriate pest-control methods: Chemical treatment to eradicate the pests nesting in the exhaust ports and a physical method to prevent field-living pests from entering the warehouse. The data are given in Table 2. Phosphine fumigation is popular for killing pests nesting in narrow spaces in a facility (Hill, 1990). Our detection method allowed us to control the pests effectively, with minimum fumigation of a few places, which is important due to the high toxicity of the fumigant in humans (Sudakin, 2005). In addition, the electric field screen was effective at excluding pests from the warehouse. The cigarette beetles were strongly deterred from entering the electric field formed in the space between the insulated conductor wires and the earthed metal net of the screen (Video supplement available at: https://www.dropbox.com/s/yiaw39zsykya8kb/Video%20supplement%202.mp4?dl=0). Previous reports have revealed that many insects reaching these screen nets probed the internal electric field with their antennae and then left without entering (Matsuda et al., 2011; Nonomura et al., 2012). In this study, we confirmed that the red flour beetles and rice weevils similarly avoided the electric field screen. All of the pests used in this study were small enough to pass through conventional woven insect nets. The electric field screen installed to the warehouse window was clearly an effective physical barrier to the entry of these pests through the window.

Conclusion

The bio-electrostatic nature of insects in an electric field was used to construct an efficient system for specifically tracking the pests prowling in a warehouse stocking agricultural crops. The main goal of this study was to obtain continuous information on prowling pests automatically by collecting pest-specific signals from detectors set at multiple points in a warehouse. Biological discharge was the most reliable signal for this purpose, and our apparatus generated a single transient discharge signal from each pest entering a discharge detector. The electrostatic insect trap attached to the discharge detector enabled us to identify the trapped pests. Using the pest-monitoring data, the nests and invasion routes of the pests were located, and chemical and physical measures were used to control the pests nesting indoors and to prevent outdoor pests from entering the warehouse.

RECOMMENDATION

The electrostatic trap with an insect discharge recorder is a basic apparatus to be integrated into the practical pest control strategy. The apparatus is useful to automatically and continuously collect information of pest temporal and spatial movements in a warehouse, and this can enable scientists to apply most effective and realistic measures to control pests.

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