Avoidance of an electric field by insects: Fundamental biological phenomenon for an electrostatic pest-exclusion strategy

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Abstract. An electric field screen is a physical device used to exclude pest insects from greenhouses and warehouses to protect crop production and storage. The screen consists of iron insulated conductor wires (ICWs) arrayed in parallel and linked to each other, an electrostatic DC voltage generator used to supply a negative charge to the ICWs, and an earthed stainless net placed on one side of the ICW layer. The ICW was negatively charged to polarize the earthed net to create a positive charge on the ICW side surface, and an electric field formed between the opposite charges of the ICW and earthed net. The current study focused on the ability of the screen to repel insects reaching the screen net. This repulsion was a result of the insect’s behaviour, i.e., the insects were deterred from entering the electric field of the screen. In fact, when the screen was negatively charged with the appropriate voltages, the insects placed their antennae inside the screen and then flew away without entering. Obviously, the insects recognized the electric field using their antennae and thereby avoided entering. Using a wide range of insects and spiders belonging to different taxonomic groups, we confirmed that the avoidance response to the electric field was common in these animals.

1. Introduction

An electrostatic-based crop protection method was previously developed as a spore precipitation screen for fungal pathogens [1] and as an insect exclusion screen for glasshouse and warehouse pests [2]. This structure consisted of a single-charged dipolar (SCD) screen in which earthed metal nets were placed on both sides of a spore precipitator to create dielectric poles. This screen was able to capture all insect pests that passed through the screen net. In addition to insect-capture, we found that the SCD screen repels insects reaching the screen net [2,3]. The insects on the charged screen net placed their antennae inside the screen, then flew away without entering the screen. Insects apparently detected an electric field with their antennae and avoided entry. Nevertheless, this finding applied to a limited number of insect species: whiteflies (glasshouse pest) [3], and cigarette beetles and vinegar flies (warehouse and food processing factory pests) [2]. In this study, we clarify whether the insect-repelling functionality of the SCD screen is effective across insect species. We used a wide range of insects and spiders belonging to different taxonomic groups (13 orders, 45 families, 62 genera and species) and confirmed that
the avoidance response to the electric field was common across these animals.

2. Materials and methods

2.1. Electric field screen
A copper conductor wire (2 mm diameter, 0.9 m length), insulated by passing through a transparent insulator vinyl sleeve (1 mm thickness, $1 \times 10^9 \Omega$), was used to construct the SCD-screen. The insulated conductor wires (ICWs) were parallel and spaced at 5-mm intervals; they were connected to each other and to a negative voltage generator. Two earthed stainless nets were placed on one side of the ICW layer, with a separation of 3 mm (Fig. 1). The ICWs were negatively charged to dielectrically polarise the ICW insulator sleeve. The negative surface charge of the ICWs causes electrostatic induction in the earthed nets (conductor), creating an opposing surface charge on the ICW-side surface of the nets. An electric field forms between the opposing charges of the ICW layer and the earthed nets [2].

2.2. Insect avoidance assay
The avoidance assay was conducted using two pieces of apparatus: a transparent acrylic cylinder (30 cm diameter, 40 cm length) partitioned into two parts with the SCD-screen (screen-cylinder) placed horizontally, and a screen-cylinder with a straw pole placed upright on the bottom (Video supplement 1). The ICWs were negatively charged with a range of voltages (0.1–8.0 kV). Test insects were released at the bottom of the screen cylinder to observe their actions as they flew up (for flies) or climbed an erect straw (for ladybird beetles) or cylinder wall (for others) to the earthed net of the screen. The assay involved 57 insect species and 5 spider species (Table 1). These organisms were collected on the university campus throughout the year. Screens with different mesh sizes (1.6–5.0-mm mesh) were used depending on the body size of the test insects and spiders. Twenty adults were used for each insect (and spider) and per voltage tested, and the experiments were performed five times.

3. Results and discussion
The avoidance assay showed that all test insects and spiders were deterred from passing through the screen net. The initial voltage at which the insects avoided the screen net varied among species (Table 1). Insects reaching the net placed their antennae inside the screen and subsequently refused to enter. The videos show examples of these movements for a leaf beetle scrambling up a wall and a ladybird beetle climbing a straw pole (Video supplement 1). In contrast, spiders (with no antennae) inserted their legs and then moved from the screen net without entering (Video supplement 2). In all cases, this avoidance behaviour became conspicuous when increased voltage was applied to the ICW. As may be expected, smaller insects or insects with longer antennae showed avoidance behaviour for lower applied voltage. However, at >2.0 kV, all insects and spiders moved from the net immediately after they reached
it, regardless of body size. Thus, the present study demonstrates that an electric field across the screen acts as an electrostatic pest exclusion barrier. In previous papers, the electric field screen was shown to capture insects blown inside the space between the ICWs and the screen net [2,4,5]. From these results, we conclude that the insect-capturing capability of the singly charged dipolar electric field screen complements unsuccessful insect repulsion.

4. Conclusion
The aim of the present work was to generalise the insect-repellent function of an electric field screen for pest exclusion to ensure safe production and preservation of crops. A broad range of insects and spiders were used for this purpose, and all were deterred from entering the screen. At a particular voltage (2.0 kV) applied to the ICWs of the screen, the screen was effective in repelling all targets approaching the screen net. These results demonstrate the importance of pest repulsion as a primary function in physical pest management.

| Table 1. Insects avoiding a dipolar electric field |
|--------------------------------------------------|
| Order | Family | Genus and species | Common name | Voltage (kV) of avoidance |
|-------|--------|-------------------|-------------|--------------------------|
| Coleoptera | Anobiidae | Lasioderma serricorne | Cigarette beetle | 0.8 |
| | Attelabidae | Euops splendidus | Leaf-rolling weevil | 1.8 |
| | Bruchidae | Callosobrachus chinensis | Azuki bean weevil | 1.2 |
| | Cerambycidae | Chlorophorus annularis | Bamboo longicorn beetle | 2.8 |
| | | Argopistes coccinelliformis | Ladybug mimicking leaf beetle | 3.2 |
| | | Aulacophora fennoralis | Cucurbit leaf beetle | 1.3 |
| | | Chrysolina aurichalcea | Mugwort leaf beetle | 1.9 |
| | Chrysomelidae | Gallerucida bifasciata | Dioscorea leaf beetle | 2.8 |
| | | Gastrophyssa atrocyanea | Japanese green duck leaf beetle | 1.2 |
| | | Gonioctena rubripennis | Wisteria leaf beetle | 2.8 |
| | | Lema cirsicola | Leaf beetle | 2.8 |
| | | Ophebia commun | Ragweed leaf beetle | 1.2 |
| | | Coccinella septempunctata | Seven-spotted ladybird beetle | 2.4 |
| | Coccinellidae | Aiolocaria hexaspilota | Ladybird beetle | 1.2 |
| | | Epilachna vigintioctopunctata | Twenty-eight-spotted ladybird beetle | 2.4 |
| | | Harmonia axyridis | Asian ladybird beetle | 2.1 |
| | | Anosimus decoratus | Weevil | 2.5 |
| | Curculionidae | Episomus turritus | Weevil | 4.3 |
| | | Eugnathus distinctus | Weevil | 3.2 |
| | | Nesalcidodes trifidus | Snout weevil | 4.3 |
| | Elateridae | Peciocera fortunae | Click beetle | 2.1 |
| | Meloidae | Epicauta gorhami | Blister beetle | 0.4 |
| | Mordellidae | Mordella brachyura | Tumbling flower beetle | 3.2 |
| | Oedemeridae | Xanthochroa atriceps | False blister beetle | 4.5 |
| | Rhynchophoridae | Siophilus oryzae | Rice weevil | 4.5 |
| | | Plexiophthalus nigrocyaneus | Mimawari beetle | 4.5 |
| | Tenebrionidae | Tribolium castaneum | Red flour beetle | 2.4 |
| | | Ulooma latimanus | Black fungus beetle | 0.5 |
| Hemiptera | Aleyrodidae | Bemisia tabaci | Sweet potato whitefly | 0.9 |
| | Aphididae | Myzus persicae | Green peach aphid | 1.5 |
| | Cicadellidae | Nephotettix cincticeps | Green rice leafhopper | 0.3 |
| | | Bothrogonia ferruginea | Black tipped leafhopper | 0.5 |
| | | Geocoris varius | Large white-spotted seed bug | 1.2 |
| | Lygaeidae | Metonchus abbreviatus | Large white-spotted seed bug | 0.8 |
| | Pentatomidae | Eurydema rugosa | Cabbage bug | 1.1 |
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