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Article

Unattended Electric Weeder (UEW): A Novel Approach to Control Floor Weeds in Orchard Nurseries

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Abstract: This study developed an unattended electric weeder (UEW) to control floor weeds in an orchard greenhouse. The UEW was a motor-driven dolly equipped with a spark exposer. The spark exposer was constructed by applying an alternating voltage (10 kV) to a conductor net (expanded metal net). The charged conductor net (C-CN) discharged into the surrounding space. Wild oat and white clover were used as test weed species. Weed seedlings growing on the floor were grounded by the biological conductor and were subjected to a spark from the C-CN when they reached the discharge space. The spark-exposed seedlings were singed and shrunk instantaneously. In the present experiment, the UEW was remotely controlled to move on the soil-cover metal nets, which were laid on the floor to make a flat surface, in a stop-and-go manner, and to eject a spark to the weed seedlings that emerged from the floor. All of the mono- and dicotyledonous weed seedlings, which had been artificially sown on the floor, were completely eradicated using this method. Thus, this study provides an experimental basis for developing an unattended technique for controlling floor weeds in an orchard greenhouse.

Keywords: alternating voltage; arc discharge-mediated spark; *Avena fatua* L.; expanded metal net; physical weed control; *Trifolium repens* L.; unattended electric weeder; voltage amplifier

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1. Introduction

Many weed control strategies have been used by tree fruit growers, depending on the type of weed, area to be controlled, and availability and feasibility of laborers [1]. Weed control is necessary for sustainable crop production. Herbicide-based weed control is the most commonly used method in greenhouse and field crop production systems [2]. However, the intensive use of herbicides causes the emergence of many weeds resistant to major classes of herbicides [3,4]. In addition, greater public concern about the use of chemicals for managing all classes of pests (i.e., pathogens, insect pests, and weeds) has led to the development of non-chemical weed control methods [5]. Biological and physical methods have been integrated into total pest management systems as an alternative to chemicals [6].

Direct applications of living herbivorous insects [7,8] or fungal phytopathogens [9] are emerging techniques to control weeds biologically. Additionally, the use of bioherbicides provides another option for biochemical weed control. Bioherbicides include fungal phytotoxins [10,11] and plant-producing phytotoxins [12] or allelochemicals [13]. However, effective control is difficult to maintain because of the limited number of application targets, problematic preparation of the agent, and high cost; thus, little practical progress has been made using these methods. The main barrier to practical implementation is that it is difficult to integrate individual methods into large-scale weed control systems under different environmental conditions. In contrast, living and dead mulch methods [14,15] have been practically implemented because of their easy and echo-friendly use. The most basic conventional physical methods include covering the soil surface with a weeding mulch film [16,17] and mowing [18], flaming [18], heating by steam [19], hot water, or hot foam [20], and tilling practices [18].

The fruit tree growers in our districts use tilling because of the disadvantages of other methods, including mulching, which entailed frequent renewal of the mulch film due to poor durability; flaming, with the potential risk of fire; mowing, with promoted regrowth by roots left in the soil; and other methods (living or dead mulch and thermal means), because the farmers were inexperienced. However, tilling operations require year-round intensive labor. Moreover, tilling has the potential to negatively impact the surface feeder roots of fruit trees [21]. To reduce labor requirements, some studies have proposed the use of robotic [22] or electrical [23–28] weeders. However, the high cost of these machine weeders limits their use, particularly on small farms [29]. Thus, the growers requested our cooperation (Research Association of Electric Field Screen Supporter, RAEFSS) to develop a new electric system, to control weeds automatically. The RAEFSS is a private research association that educates small farmers on electrostatic-based agricultural techniques [30]. Some types of electrostatic apparatus have been launched for insect pest control in response to farmers' requests [31–33]. The present study was conducted to meet the demands of farmers.

The arc discharge-exposure method for weed control was originally developed by Wilson and Anderson [23]. The principles of electricity used for weed control are provided in previous studies [34,35], where weeds at the soil-emerging stage were killed by directly exposing young shoots to a high-voltage arc (spark) discharge. Arcing is an electrical phenomenon generated by the movement of a high-voltage-mediated negative charge in the air between opposite electric conductors [36]. The soil-emerging weed shoots act as biological conductors that receive the discharge from a charged conductor [34]. This technique has been successfully applied to control kudzu (*Pueraria. montana* var, lobata [Willd.] Ohwi) creeping along an animal-repelling electric fence [37] and for weed populations growing in crop fields [35]. These approaches suggest that a simple electric weed eradicator could be fabricated easily and inexpensively.

The present study aimed to develop an unattended method to control floor weeds in an orchard greenhouse. Thus, we fabricated a motor-driven dolly equipped with a spark-exposing apparatus (charged metal net), clarified the optimal conditions for killing mono- and dicotyledonous weed seedlings using the spark exposure treatment, and applied the system to control weed seedlings growing on the greenhouse floor by automatically moving the electric weeder. Based on these results, we evaluated the feasibility of the present method for controlling floor weeds in an orchard greenhouse and provide an experimental basis for developing an unattended electric weeding system.

2. Materials and Methods

2.1. Plant Species

Wild oat (*Avena fatua* L.) and white clover (*Trifolium repens* L.) were used as the model mono- and dicotyledonous weed species. The seeds (Takii & Co., Ltd., Kyoto, Japan) of these plants were sown in plastic trays containing soil, and elongated seedlings were used for the spark-exposure experiment in the laboratory. The seeds were sown directly on the greenhouse floor for the unattended weed control approach.

2.2. Experimental Instruments Used to Expose the Plant Seedlings to an Electric Spark

2.2.1. The Charged Conductor Net and Determining the Spark Distance

An expanded stainless net (60 × 50 cm^2; strand thickness, 0.8 mm) (Okutani Wire Netting Mfg., Co., Ltd., Kobe, Japan) (Figure S1A) was used as the charged conductor net (CN). Alternating voltage was applied to the CN using a voltage amplifier (VA) (useable voltage, 10 kV; maximum current, 120 mA; 10 kHz) (Logy Electric Co., Ltd., Tokyo, Japan). The VA was linked to a grounded line, which was connected to a ground-contact wall socket, and its charging probe was linked to the CN (Figure S2A). The charged conductor (C-CN) formed a discharge space in the surrounding air (Figure S2A). The expansion of the discharge space was determined by the voltage applied to the conductor [38].

The charged conductor discharges when the grounded conductor reaches the discharge space and causes an arc discharge in the air between the charged and grounded conductors. The arc discharge of the charged conductor is an electric phenomenon in which the high-voltage negative charge moves in the air with an instantaneous spark (spark discharge) [36]. In this experiment, we determined the distance between the C-CN and the grounded conductor required to cause a successful spark by the C-CN. An iron nail (5 cm length; 1 mm thickness) was connected to a grounded line and used as a grounded conductor. The C-CN was held horizontally with a plastic (polypropylene) clamp (insulator), and the grounded nail was vertically held under the C-CN (Figure S2B). The grounded nail was gradually brought closer to the C-CN to determine the point at which the spark discharge occurred (Figure S2C). Thus, we determined the longest distance (4 mm) from the C-CN (the edge of the discharge space) required to cause the spark discharge toward the grounded conductor.

2.2.2. Double-Net System for Exposing Plant Seedlings to an Electric Spark

In this experiment, we used wet soil in a plastic tray (61 × 51 cm^2; depth, 2 cm). The soil was grounded by contacting a grounded line that was introduced from the side wall of the tray (Figure 1A). Germinating wild oat and white clover seeds were sown in the soil, and a second expanded metal net (60 × 50 cm^2; strand thickness, 2.0 mm) (Figure S1B) was placed on the soil as a soil-cover net to create a flat and horizontal surface (Figure 1A). Seedlings that grew to 3–6 mm high from the upper surface of the soil-cover net were used for the spark exposure treatment. Namely, the C-CN (not charged) was held horizontally and set above the seedling-growing tray at an interval of 6 mm (discharge space of 4 mm and non-contact space of 2 mm) between the C-CN and the soil-cover net (Figure 1A). Then, the VA was switched on to charge the C-CN.

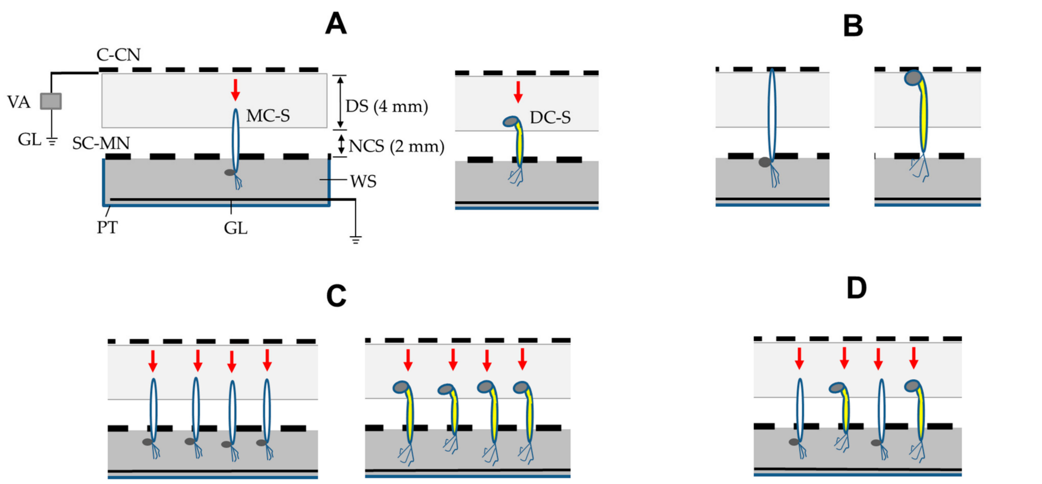

Figure 1. Exposure of wild oat (MC-S) and white clover (DC-S) seedlings to an electric spark generated by a charged conductor net (C-CN). (**A**) Spark exposure of single MC-S (**left**) and DC-S (**right**) that did not reach the C-CN. The C-CN was linked to a voltage amplifier (VA) and formed a 4-mm wide discharge space (DS). The soil-cover metal net (SC-MN) was placed on the wet soil (WS) in a plastic tray (PT) to make a flat surface. Seeds of the test plants were sown in the soil, which was in contact with a grounded line (GL) that was introduced from the tray wall. The distance between the C-CN and the SC-MN was fixed at 6 mm. (**B**) Exposing a single seedling to the spark that reached the C-CN. (**C**) Exposing multiple seedlings (2–20 seedlings) to the spark. (**D**) MC- and DC-Ss were exposed to sparks and growing on the same tray. The red arrow represents the spark from the C-CN to the seedling.

In the first experiment, we exposed single wild oat and white clover seedlings that had reached the discharge space, but not the C-CN (Figure 1A). The coleoptile and hypocotyl were the spark-exposed sites of these weeds, respectively. As the spark exposure stopped automatically, we measured the duration of the spark exposure to compare the tolerance between the two weed species. In the second experiment, the seedlings that had reached the C-CN were similarly treated to compare the time of spark exposure between them and between the C-CN-touched and untouched cases (Figure 1B). In both experiments, 20 seedlings were used for each weed species, and the experiments were repeated five times. In the third experiment, multiple seedlings growing on the same tray were exposed to the spark (Figure 1C). Namely, we prepared 10 groups, which contained 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 seedlings on the tray, and placed each group beneath the C-CN for spark exposure. As the sparks were launched one by one or stepwise toward all seedlings and then stopped automatically, the duration of the spark exposure was examined to determine the relationship between the time of spark exposure and the number of seedlings of each weed species used. Additionally, we conducted a similar experiment for the wild oat and white clover seedlings that were grown half-and-half on the same tray. All experiments were repeated five times.

2.3. Construction of a Motor-Driven Dolly Carrying the C-CN and Its Application to Greenhouse Floor Weeding

2.3.1. Construction of the Unattended Electric Weeder

We installed the C-CN on a motor-driven dolly (floor area, 70 × 90 cm^2) (Figure 2A). The C-CN (60 × 50 cm^2) was horizontally attached to the outer surface of the bottom of the dolly; the discharge space was formed between the C-CN and the soil-cover metal net that was laid on the ground (Figure 2B). The movement of the dolly was remotely controlled by a motor-operating controller linked to the dolly with a coiled extension electric cable. The C-CN-equipped dolly was used as an unattended electric weeder (UEW) to control floor weeds in an orchard greenhouse.

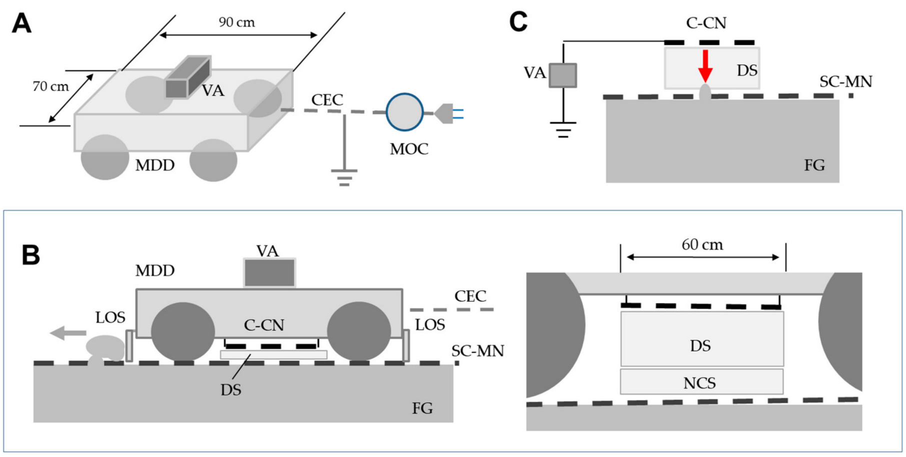

Figure 2. (**A**) A motor-driven dolly (MDD) carrying a charged conductor net (C-CN). (**B**) Cross-sectional view of the MDD. The C-CN was linked to a voltage amplifier (VA) and equipped on the outer surface of the bottom of the dolly. The discharge space (DS) (4 mm wide) was formed in the space between the C-CN and the soil-cover metal net (SC-MN) laid on the floor (FG). The interval between the C-CN and the SC-MN was fixed at 6 mm, including 4 mm of DS and 2 mm of non-contact space (NCS). The level-off-soil sliders (LOSs) were equipped in the front and back of the dolly. The dolly was remotely operated by a motor-operation controller (MOC) that was linked with a coiled extension electric cable (CEC). (**C**) Exposing the soil to a spark that protruded from the SC-MN. The soil over the SC-MN reached the DS to receive the arc-discharge-mediated spark (red arrow) from the C-CN. Extra soil over the SC-MN was removed by the LOS when moving (gray arrow) the dolly (**B**).

2.3.2. Level-Off-Soil Operation to Avoid Undesired Sparking of the Ground Soil

Five soil-cover metal nets (each, 1 × 1 m^2) were laid on the greenhouse floor to make the floor flat for the UEW. However, the problem was that the ground soil protruded from the upper surface of the CN, as these soils reached the discharge space to receive the spark from the C-CN (Figure 2C). To avoid this undesired sparking, we attached flat plates to the front and back of the dolly to level off the soil (Figure 2B). The extra soil on the soil-cover metal net was pushed away as the dolly moved (Figure 2B). This leveling-of-soil operation readied the discharge space beneath the C-CN to expose only plant seedlings to the spark. As the arc discharge was always accompanied by a specific sound (arc-discharge sound) [28,29,31], effective elimination of the extra soil was confirmed by checking for the presence or absence of the arc-discharge sound by moving the UEW over the soil-cover metal net at the stage before the weed seedlings appeared.

2.3.3. Application of the UEW to Control Floor Weeds in a Greenhouse

The UEW (Figure 3A) was used for unattended control of floor weeds in a greenhouse. Seeds (300, 600, and 900 seeds) of the test weeds were mixed half and half and sown directly in the seeding area (SA1–3) (each 60 × 100 cm^2) on the greenhouse floor. The seeded areas were covered with soil-cover metal nets (1 × 1 m^2) in a row (Figure 3B). Two additional nets were placed on both sides of the net row to prepare the departure and arrival places for the UEW. The movement of the UEW was controlled remotely using a motor-operated controller. The UEW was moved over the connected soil-cover nets from one end to the other in a stop-and-go manner: 5 cm/s for 10 s and stopping for 3 min. The UEW traveled forward (Figure 3B) and returned (Figure 3C) using the same route. This go-and-return movement of the UEW was repeated twice daily (morning and evening) for 1 week. The exposure treatment started when the first seedling appeared on the soil-cover nets and continued for 1 week. The numbers of seedlings (1) exceeding the C-CN (ECCN-seedlings), (2) reaching the discharge space (RDS-seedlings), and (3) not reaching the discharge space (URDS-seedlings) were counted using a leveling-wire stand (Figure 3C) each day after the evening treatment was completed. As a control, three seeding areas covered with nets were similarly prepared in the neighborhood, but the spark-exposure treatment was not applied. The numbers of whole weeds and ECCN seedlings were counted each day during the experimental periods. Separate experiments were replicated five times. The experiments were carried out from July to August 2022. The diurnal change in the greenhouse temperature and relative humidity during the experimental periods was 16 to 36 °C and 48 to 98%, respectively.

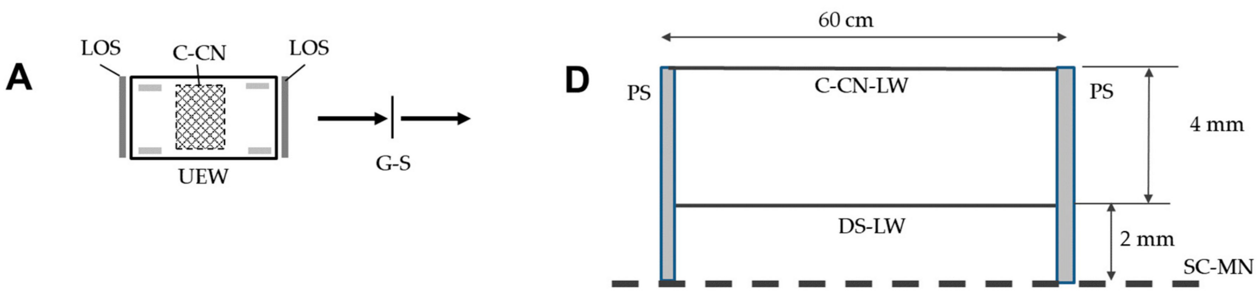

Figure 3. *Cont.*

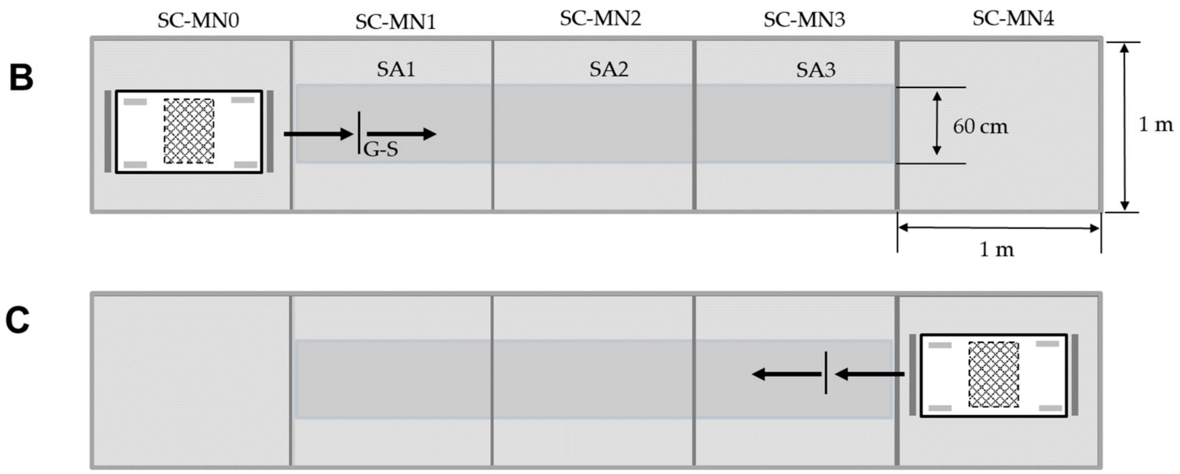

Figure 3. Design of the spark-exposure treatment of greenhouse floor weeds with an unattended electric weeder (UEW). (**A**) A bird's-eye view of the UEW equipped with a charged conductor net (C-CN) and two level-off-soil sliders (LOSs). (**B**,**C**) Weed seeding, placement of the soil-cover metal nets (SC-MNs), and movement of the UEW. Seeds were sown in the seeding areas (SA1–3) of the greenhouse floor, and three SC-MNs nets (SC-MN-1–3) were laid over SA1–3 in a row, respectively. An additional two nets (SC-MN-0 and 4) were placed on both sides of the net row to make departure and arrival places for the UEW. The UEW was moved over the connected SC-MNs from one end to the other in a stop-and-go manner (G-S). The UEW was remotely controlled to go forward (**B**) and return (**C**) on the same route. (**D**) A leveling-wire stand to examine the height of the seedlings (cross-sectional view). Two iron wires (C-CN- and DS-LW) were bridges between two identical plastic stands (PSs) 2 and 6 mm above the SC-MN, respectively. The leveling-wire stand slid on the SC-MNs and allowed the height of each seedling to be checked.

2.4. Statistical Analysis

All experiments were repeated five times, and the data are presented as mean ± standard deviation. Tukey's test and linear regression analysis were performed using EZR software v1.54 (Jichi Medical University, Saitama, Japan) [39] to detect significant differences between conditions and the correlations among the factors.

3. Results

3.1. Sparking Distance of the C-CN

The primary objective of the present study was to determine the sparking distance of the C-CN. The sparking distance was determined by the voltage applied to the conductor. A conductor charged with a higher voltage produces a wider discharge space in the surrounding area [38]. The spark discharge of the C-CN occurred the moment the pointed tip of the grounded iron nail reached the outer edge of the discharge field (4 mm from the C-CN). This distance was considered the C-CN sparking distance. The importance of the sparking-distance specification was to make it possible to construct an apparatus that ejects a discharge-mediated spark to every grounded conductor that comes into an area within 4 mm from the C-CN. As plant seedlings growing on the ground are grounded biological conductors [34], they can be targeted for the spark by the C-CN.

3.2. Exposure of Plant Seedlings to an Arc Discharge-Mediated Spark

Previous studies [34,35] have suggested that the spark-exposure treatment effectively kills weed seedlings. Thus, we evaluated the effectiveness of an electric spark produced by the present apparatus. In the first experiment, we ejected the spark to single wild oat and white clover seedlings to determine the destructive power of the electric spark. Video S1A,B demonstrates that the energy of the electric spark was highly destructive; the white clover seedlings were singed instantaneously, while the wild oat seedlings were singed and shrunk after a short exposure. These results strongly suggest the involvement of current-flow-mediated heating (Joule heating) [40] during this type of seedling destruction. These results also indicate that there was a significant difference in the time of spark exposure between the two weed species (Figure 4). The spark exposure of the white clover seedlings stopped in less than 1 s, whereas the exposure of the wild oat seedlings continued for 5–7 s. This result suggests that the different tolerances of the two weed plants were due to different electrical characteristics of the coleoptiles (wild oat) and hypocotyls (white clover of the seedlings that received the spark. The hypocotyls were more susceptible to spark exposure than the coleoptiles (Video S1B). We considered that the hypocotyls of the white clover seedlings were more conductive than the coleoptile tissue of the wild oat seedlings and, therefore, larger amounts of electric current caused rapid destruction of the white clover seedlings. In addition, we spark-exposed single wild oat and white clover seedlings that reached the C-CN. Video S1A,B shows that similar destructive effects were detected on these two seedlings when they touched the C-CN. Figure 4 indicates no significant difference in the duration of the spark exposure between the seedlings that touched and did not touch the C-CN in either weed species. We concluded that the present apparatus could handle the seedlings that exceeded the C-CN as well as the seedlings beneath the C-CN.

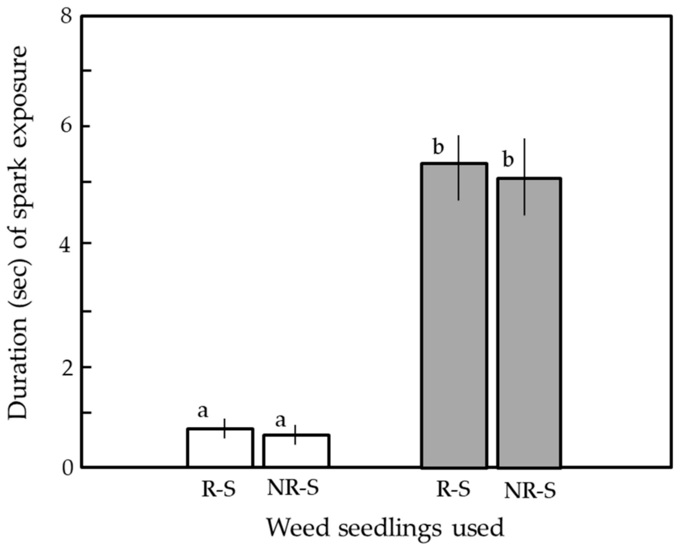

Figure 4. Comparison of the duration of spark exposure of a single white clover (open) and wild oat (gray column) seedlings. R-S and NR-S denote the seedlings that reached and did not reach the charged conductor net, respectively. Twenty seedlings were used for each weed species. Mean and standard deviation values were calculated from five experimental replicates. Different letters (a, b) in each vertical column indicate significant differences ($p < 0.05$) according to Tukey's test.

The main objective of the present experiment was to determine the size of the target population, i.e., the maximum number of weed seedlings that the present apparatus could treat at one time. Thus, we exposed multiple wild oat and white clover seedlings to sparks. The results indicated that there were two spark exposure methods for these plants. Video S2 shows the cases of three wild oat and white clover seedlings. The white clover seedlings were subjected to the spark in a one-by-one manner from the tallest seedling. The seedlings were knocked down by a single spark discharge (Figure S3A). In contrast, the exposure was first directed to the tallest wild oat seedling. However, the exposure was turned to the second tallest and then the third tallest seedling when the height of the first seedling became smaller than these seedlings, and finally returned to the first seedling (Figure S3B). Spark exposure continued until all seedlings were short of the C-CN discharge space. These two types of spark exposures included all cases of both weed species, regardless of the number of seedlings applied.

For the linear regression analysis between the number of the seedlings applied and the time length of the spark exposure, until the exposure stopped automatically, we exposed multiple seedlings (2–20 seedlings) of the test weeds to the spark and measured the duration of spark exposure. Figure 5 shows the results of the wild oat (A), white clover seedlings (B), and a half-and-half mixture of the two weed species (C). In each case, the R-squared value represented a relatively good fit of the line to the data; as the number of the seedlings treated increased, a longer spark exposure treatment was required to eradicate all of the seedlings. Thus, this trend was useful to illustrate the predicted treatment time length in response to an increase in the weeds growing on the floor area.

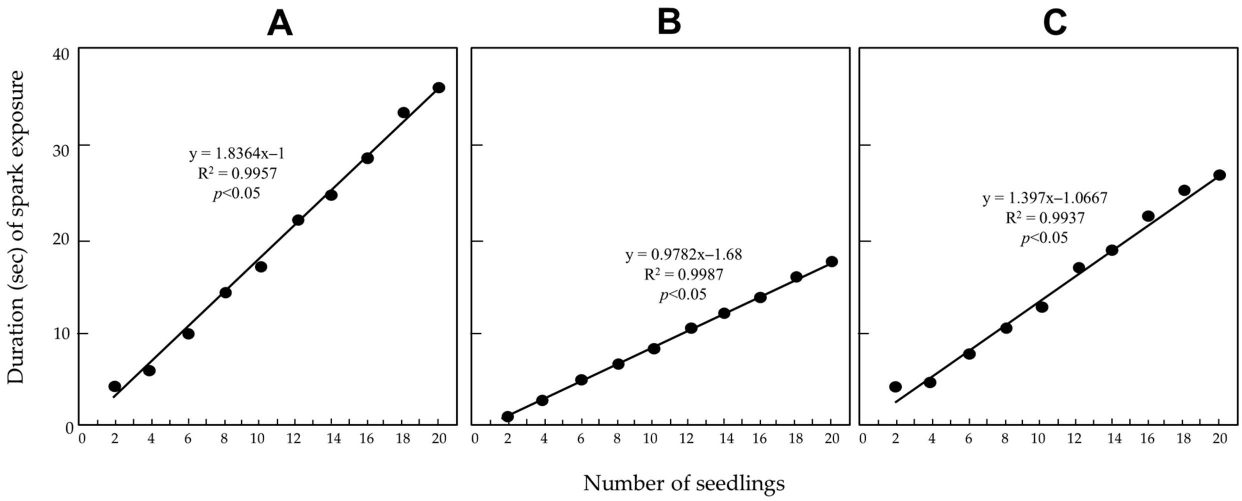

Figure 5. Relationship between the number of weed seedlings and the duration of spark exposure. (**A**,**B**) represent a group of wild oat and white clover seedlings, respectively. (**C**) represents a group that contained half wild oat and half white clover seedlings. Note that each of the R-squared values (0.9957, 0.9987, and 0.9937) obtained was a relatively good fit with the line to the data.

The present study revealed that current-flow-mediated heating was the key mechanism for destroying weed seedlings. Based on this interpretation, the weed destruction efficiency was dependent on the output voltage and current of the apparatus. This was a problem of the VA used in the present study. The maximum output of the present VA was 10 kV/120 mA, which was the limit of the working capacity of the apparatus. We searched for the optimal weeding conditions.

3.3. Application of the UEW to Control Floor Weeds in a Greenhouse

3.3.1. Prerequisite Operations before the Spark-Exposure Treatment

The greenhouse floor can be used as a grounded conductor if the soil is sufficiently wet. Matsuda et al. [34] reported that free water in the ground soil easily evaporates through a low-temperature (30 °C) dehydration procedure and that the soil loses conductance when 60% of the free water is lost by evaporation. Water in the superficial soil layer easily evaporates, particularly during the high-temperature season. Many weeds live in this soil layer, so keeping the soil wet was essential to ensure successful current flow from the spark-exposed plant seedlings to the ground via the floor soil [34]. Thus, watering the floor is an effective way to ground the floor soil; that is, to ensure satisfactory spark-exposure efficiency.

The second prerequisite was the trial run of the UEW to level off the extra soil that protruded from the soil-cover metal net on the floor. The level-off-soil slider attached to the UEW was an effective way to push the soil away (Figure 2B), by which the C-CN was allowed to preferentially eject the spark to target plant seedlings during the spark-exposure treatment.

3.3.2. Greenhouse Assay for Controlling Floor Weeds by the UEW

We developed an unattended method to control weed seedlings growing on a greenhouse floor by automatically moving the UEW in a stop-and-go manner. We had two basic problems applying the present system. The first problem was the number of seedlings that the UEW could treat at one time. The most important parameter was the stopping time, as the spark-exposure treatment was performed while the UEW was stopped. In this experiment, we determined the required exposure time by predicting the number of seedlings involved in the C-CN (60 × 50 cm^2) sparking area (Figure 5). Our preliminary observations showed that the emergence rate of the seeds was approximately 90% for both weed species and that these seedlings appeared successively on the ground over 5 days. Based on this observation, we calculated the exposure times (UEW-length of stop time) from the case that 900 seeds (the highest number) of the wild oat required longer exposure times than the white clover were sown. As a result, the UEW C-CN was expected to encounter a maximum of approximately 80 seedlings per stop. Judging from the wild oat trend (Figure 6A), a 3 min exposure would be long enough for the UEW to treat all 80 wild oat seedlings during one stop. The second problem was that the URDS seedlings (seedlings that had not reached the discharge space yet) comprised the majority. The UEW passed over these seedlings without ejecting a spark. Nevertheless, the rapid growth of weed seedlings helped solve this problem. In our preliminary observations, the weed seedlings elongated 2–4 mm per half day and, therefore, the URDS seedlings were expected to grow to be RDS seedlings in half a day. It was possible to treat these seedlings by weeding in the morning and evening. We applied the go-and-return movement of the UEW (Figure 3B,C) twice per day in the morning and evening for 1 week.

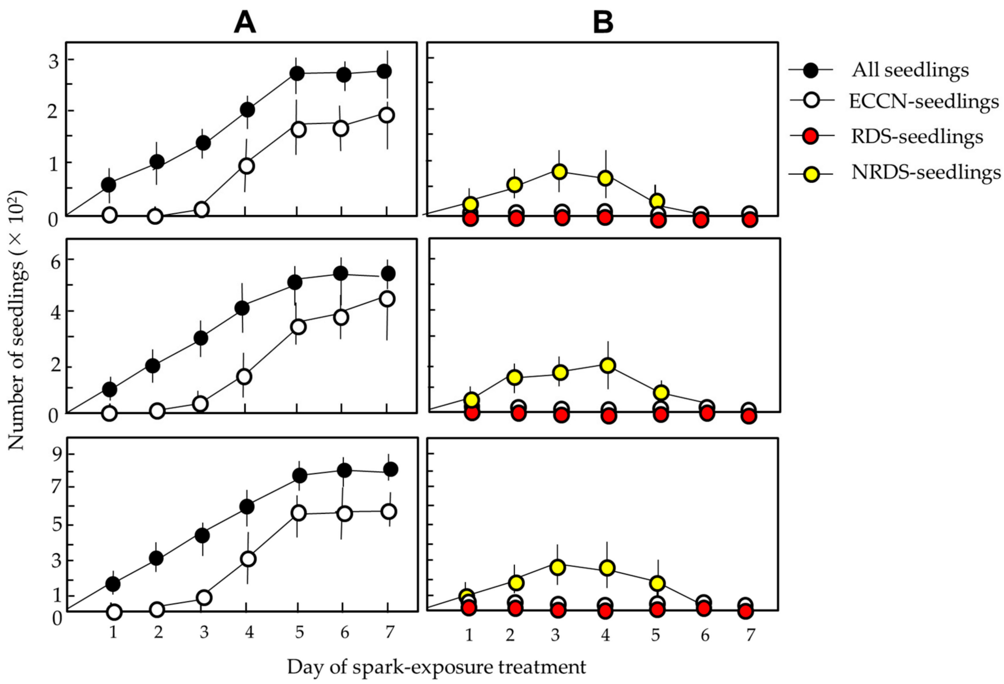

Figure 6. Treatment of the weed seedlings with a spark generated by the charged conductor net (C-CN) on the unattended electric weeder (UEW). The upper, middle, and lower panels represent the seeding area (SA1–3), where 300, 600, and 900 seeds of wild oat or white clover were sown half and half, respectively. (**A**) Untreated weed seedlings that were grown on the greenhouse floor were covered with an expanded metal net (control). (**B**) Weed seedlings that were exposed to a spark from the UEW that was automatically moved over the metal nets laid on the seeding area. ECCN, RDS, and URDS seedlings represent the seedlings exceeding the C-CN, reaching the discharge space of the C-CN, and not reaching the discharge space, respectively. Means and standard deviations were calculated from five experimental replicates.

Figure 6 shows the results of the spark-exposure treatment for the weed seedlings on the greenhouse floor. In this experiment, different numbers of wild oat and white clover seedlings (300, 600, and 900 seedlings in seeding areas SA1, 2, and 3) were used. The weed seedlings in the untreated control (Figure 6A) appeared successively between D1 and D5 and rapidly elongated 4–8 mm per day; the seedlings (ECCN seedlings) that exceeded the height of the C-CN first appeared at D4 and increased rapidly thereafter. Neither the RDS nor the URDS seedlings were counted in the untreated seeding area because it was difficult to distinguish them among the numerous vigorously growing seedlings. As a result, the rates of the seedlings that developed from seed were 90.8 ± 2.5% for the wild oat and 89.3 ± 4.3% for the white clover in the three seeding areas from five separate experiments.

Figure 6B shows the number of seedlings that were still living after two spark-exposure treatments per day. The most important point was that the taller seedlings (ECCN and RDS seedlings) were not detected in the three seeding areas throughout the entire experimental period, suggesting that the apparatus controlled all of the ECCN and RDS seedlings that appeared on these days. Thus, two (morning and evening) treatments were highly effective to catch up with the URDS seedlings that escaped from the earlier exposure treatment. Figure 6A shows that the newly elongated seedlings appeared successively between days 1 and 5. All of these seedlings grew into the discharge space on days 6 and 7 and were subjected to the spark. All of the seedlings were eventually eradicated by the UEW, twice per day, for 7 days. The spark exposure treatment was effective, regardless of the number of seedlings and different weed species. Figure 7 is an illustrative example of a successful application of the present method to the floor weeds in a greenhouse. The photograph shows the situation on day 7; two rows of the soil-cover metal nets were arranged in parallel on the floor for an easy comparison of the effect (Figure 7A). One row was the untreated control, where the weed seedlings had elongated vigorously depending on the number of seeds sown (300, 600, or 900 seeds in the SA1 to 3, respectively), and the other was the row for the spark-exposure treated division, in which all of the seedlings were effectively eradicated by the treatment (Figure 7A,B). Thus, these results indicate that the unattended method using the UEW was practical for controlling floor weeds in a greenhouse.

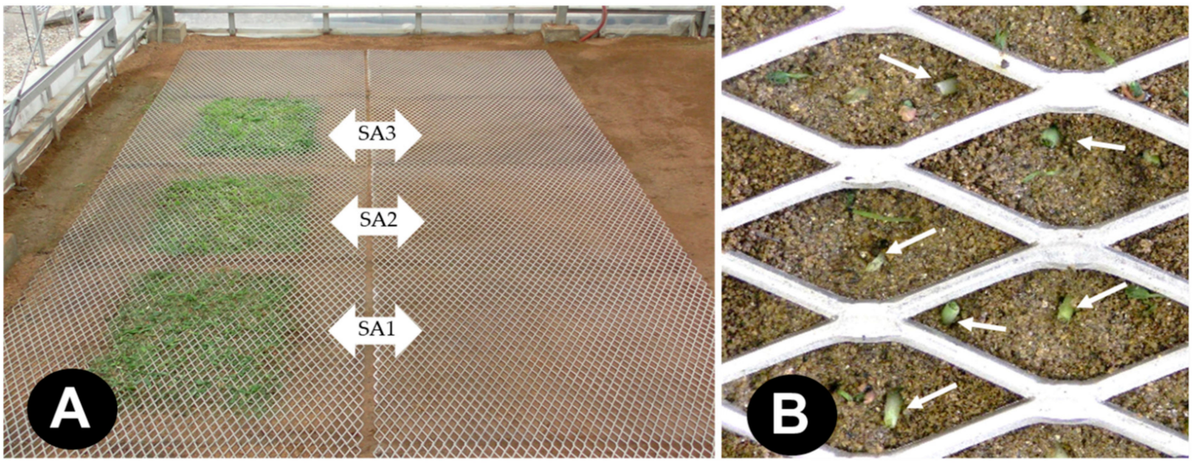

Figure 7. Eradication of weed seedlings growing on the floor of a greenhouse with an unattended electric weeder. (**A**) Two rows of connected soil-cover metal nets were arranged in parallel on the floor of the greenhouse. The left row was for the untreated weed seedlings (control), and the right row was for the seedlings that were treated with sparks twice a day for 1 week. No seedling appeared in the seeding area (SA1–3) on the right-side net row, in contrast to the vigorous growth of the seedlings in the neighboring control. (**B**) A close-up of the ground surface beneath the soil-cover metal net shows weed seedlings (arrows) damaged severely by the spark-exposure treatment.

4. Discussion

In the present study, we successfully fabricated a remotely controlled motor-driven dolly that was equipped with a spark-exposure apparatus, demonstrated the ability of the apparatus to kill weed seedlings, and provided an experimental basis for applying the present method to floor weed control in an orchard greenhouse. In addition to this technical progress, many growers have an overriding concern about the costs of manufacturing the UEW and purchasing the soil-cover metal nets. To fabricate the UEW, we purchased a motor-driven dolly and a voltage amplifier. The C-CN, which is the heart of the UEW, was easily installed by linking a flat metal net to a voltage amplifier with an electric wire and attaching it horizontally to the outer surface of the bottom of the dolly. In fact, the expense necessary for preparing the UEW was only the cost of materials, which was approximately \$1500 in U.S. dollars. The costs for the metal nets vary with the size of the floor covered. In our ordinary orchard greenhouse (floor area, 20×20 m^2), approximately 250 metal nets were needed to cover the floor for weeding, and the cost was estimated at approximately \$2000 (approximately \$8 per square meter). Eventually, the growers may be costed this amount of expenses to perform the present system in a greenhouse.

Although the present study revealed that this method can be used to manage mono- and dicotyledonous weed species effectively, some questions need to be clarified in our subsequent study. Our concern now involves how to use this method to control creeping perennial weeds with subterranean stems or rhizomes in the floor [21]. To solve this problem, it may be useful to clarify the conductivity of weed seedlings, which is an issue pertaining to how long the electric current flows in the weed body. The present results suggest that the portions of the weed bodies in which electric current flowed were passively destroyed. Another concern is the possibility of inter-root transfer of a negative charge, particularly between the roots of weeds and young fruit trees. As their root systems may be intertwined in a superficial layer of the soil [21], clarifying this problem would avoid the undesired effects of a negative charge that flows through weed roots reaching the roots of a fruit tree.

The present method required a flat floor surface. Thus, we laid several expanded metal nets on the floor area to be weeded. The metal nets used in this study (2 mm strands) were sturdy enough for workers to conduct operations on the nets. This allowed us to leave the metal nets there throughout the year. Nevertheless, we have no information about how the present metal nets bear the load of heavier farm equipment used in a greenhouse cropping system. Further investigations are required to answer this question. Our orchard greenhouse was an ideal place to lay the metal nets on the floor because there are no ridges for crop cultivation. However, this advantage may be an obstacle to broad applications of the present method to other field and greenhouse crop production systems. In particular, a new device for curved portions, such as a cropping ridge, is essential for this purpose.

Applying the UEW for floor weed control in an orchard greenhouse was expected to reduce labor. From this viewpoint, we designed the next study. The purpose of the study was to completely automate weeding operations and optimize the system. Thus, we used a storage battery-operated VA to save energy and a wireless apparatus for sending and receiving signals to remotely control the movement of the UEW. Then, we examined the relationships between weeding efficiency and (1) the voltage applied, (2) the size of the spark-exposed area (the area of the C-CN), (3) the length of spark exposure (length of stop time), (4) the number and timing of the weeding operations during a day, and (5) the age and types of and population size of the weeds to be targeted. The final purpose was to program a computer with these data for automatic weed operation in the future.

5. Conclusions

We have presented a remote-controllable electric weeder armed with a spark-exposing apparatus. The spark-exposure treatment was highly effective for killing weed seedlings instantaneously, regardless of the cotyledon type. Operation of the weeder was programmed based on the diurnal elongation of the weed seedlings and effectively killed the seedlings that emerged on the greenhouse floor ground at different times. The use of this weeder is expected to lighten weeding labor by growers. The structure of the weeder is simple, and the parts of the apparatus are affordable, such that the growers could fabricate the weeder without any special skills. Thus, the present study provides beneficial information for realizing the unattended control of floor weeds.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13071954/s1, Figure S1: The two expanded stainless nets were used for the present study, Figure S2: Charging of the conductor metal net with an alternating voltage amplifier (VA) and a spark generated by a charged conductor net (C-CN), Figure S3: Exposing three white clover (A) and wild oat (B) seedlings to a spark generated by a charged conductor net (C-CN), Video S1: Wild oat (A) and white clover (B) seedlings exposed to the spark from a charged conductor net (C-CN), Video S2: Three white clover (A) and wild oat clover (B) seedlings were exposed to a spark from the charged conductor net (C-CN).

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