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Use of Pulsed Arc Discharge Exposure to Impede Expansion of the Invasive Vine *Pueraria montana*

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Abstract: The invasive kudzu vine *Pueraria montana* var. *lobata* is an agricultural nuisance that disturbs the field cultivation of crop plants. We developed a simple electrostatic method of suppressing the invasive growth of kudzu vines as an alternative to the use of herbicides for weed control. Exposure of the vine apex to a high-voltage arc discharge was the focal point of the study. To achieve this, we constructed a ladder-shaped apparatus by arranging several parallel copper rods at specific intervals in an insulating frame. The top rod was linked to a direct current voltage generator and pulse-charged at −10 kV, and the remaining rods were linked to a grounded line. Because of the conductive nature of the grounded vine body, the vine climbing along the grounded rods was subjected to a pulsed arc discharge from the charged rod when its apex entered the electric field produced around the charged rod. The part of the vine exposed to the discharge was heated, which promoted vaporisation of body water. This destroyed the tip growing point and prevented vine elongation. A simplified weed control apparatus was developed, which can be fabricated for practical use from inexpensive, ready-made materials.

Keywords: electrostatic apparatus; weed control; electric fence; thermographic analysis; sound intensity analysis

1. Introduction

Tomato plants have been farmed organically in our laboratory under both greenhouse and field cultivation conditions. For the greenhouse tomatoes, we have developed physical (electrostatic) methods of controlling airborne fungal pathogens [1–3] and flying insect pests [3–5] that pass through a conventional insect-proof net as an alternative to the use of pesticides. In the field, we have grown numerous wild tomato species under constant exposure to natural infection by pathogens and/or attacks by insect pests to breed tomato lines resistant to pathogens and insects. Unfortunately, our field cultivation has frequently been disturbed by agricultural nuisances such as wild animals and invasive plant creepers (kudzu) because our experimental fields were created by clearing part of a forest. We have successfully repelled wild animals using an electric fence, but we have had no effective means of impeding the invasive expansion of plant creepers under our herbicide-independent organic farming conditions.

Kudzu or Japanese arrowroot (*Pueraria montana* var. *lobate* [Willd.] Ohwi) was originally cultivated to harvest starch [6] and various medicinal phytochemicals [7] to supply livestock feed [8–11] as a source of biofuel [12], and to control land greening or land erosion in desert areas [13]. However, the use of kudzu has declined in recent years, and the plants have been abandoned without being controlled properly. As a consequence, they have become a major weed species that flourishes vigorously across Japan.

Kudzu is an interesting plant that shows specific growth and differentiation patterns in response to seasonal change in the environment [14]. In warm and hot seasons, the plant spreads vigorously through vegetative reproduction via runners (stolons) that form new plants and roots at the nodes. The plant invasively trails perennial vines that cover trees or shrubs, which are then killed by the heavy shading [15,16]. In addition to disturbing the ecological balance, these noxious weeds cause environmental and social problems [17]. This can include coiling and climbing up electric poles to overhang bridged aerial power lines or cover traffic signs or trailing over fences and covering slope faces along electric railway tracks and motorways. It has, therefore, become important to control the kudzu plant for landscape preservation. In late autumn, morphological changes induced in the vines of the plant ensure its perennial nature. These changes are vital to the plant's survival under cold conditions. If they are effective, the plant will live through the winter and generate new plantlets and runners on its perennial vine nodes in the next growing season [18]. Eventually, this convertible differentiation system of the kudzu plant perpetuates the spoilage of natural ecosystems through the invasive growth of creepers.

The main method of controlling kudzu plants is to apply herbicides [19–21]. Some systemic herbicides can be applied directly on cut kudzu stems to be transported into the plant's extensive root system. Herbicides are more effective after other methods (e.g., mowing, grazing, and burning) have been used to weaken the plants [22]. The use of bio-herbicides is an additional option for controlling kudzu plants, and these can be applied in combination with other control measures [21,23–25]. After an initial herbicidal treatment, follow-up treatments and monitoring are usually necessary, depending on how long the kudzu plants have been growing in a particular area. Unfortunately, this is not always practical because of the massive cost and labour required to control kudzu plants growing over vast areas [26,27].

Herbicides are the predominant method of controlling weeds in modern agriculture. However, their overuse has led to the rapid evolution of herbicide-resistant weeds [28]. Given the problem of herbicide resistance and the long-standing public concern to reduce overall pesticide use, alternatives to herbicides and truly integrated weed management strategies are urgently required. Therefore, we developed a new physical (electrostatic) method as an alternative to the use of herbicides.

The electrostatic method devised for weed control was based on the conductive nature of grounded plants. In a previous study [29], we found that a discharge-generating electric field was formed between a grounded plant and a negatively charged metal needle brought close to the plant. This implies that negative electricity (free electrons) accumulated on the pointed tip of the needle pole positively polarised the plant by electrostatic induction (i.e., these opposite charges formed the electric field between them). In a high-voltage electric field, the electricity on a needle pole is transferred to the ground via a ground-linked plant body. This transfer of electricity occurs through an arc discharge of the needle pole [30]. Thus, free electrons that are accelerated by a high-voltage pass through the plant body in the electric field are expected to have detrimental effects on the survival of the plant.

In this study, we designed a simple electric field-based apparatus to impede invasive expansion of the kudzu vine. For this purpose, we developed a plant-mediated arc discharge between a negatively charged metal conductor and a plant in contact with the grounded conductor. Young saplings that were developing vines were used to examine the generation of the arc discharge between the apical tip of the grounded vine and the conductor wire that was pulse-charged with the negative voltage.

In this practical application, we used a pulse-charging-type voltage generator, which is commonly used in electric fences to repel wild animals for safety reasons. Based on the results we obtained, we propose a simple and unique physical tool for selectively exposing vines of the kudzu plant to a high-energy electric current from a charged conductor, immediately destroying the vines. This method is a promising tool for impeding the invasive expansion of kudzu vines.

2. Materials and Methods

2.1. Plant Material

Saplings of kudzu (*P. montana* var, *lobata*) were propagated by cuttings because of the low seed germination rate [31]. Vine stems (8–10 cm long) containing single hibernating nodes were detached from kudzu plants growing naturally on a university campus (Nara Prefecture, Japan). The nodes were potted and grown in a sunny greenhouse to generate a new plantlet and vine out of the node (Figure 1A). These saplings were used in the following experiments.

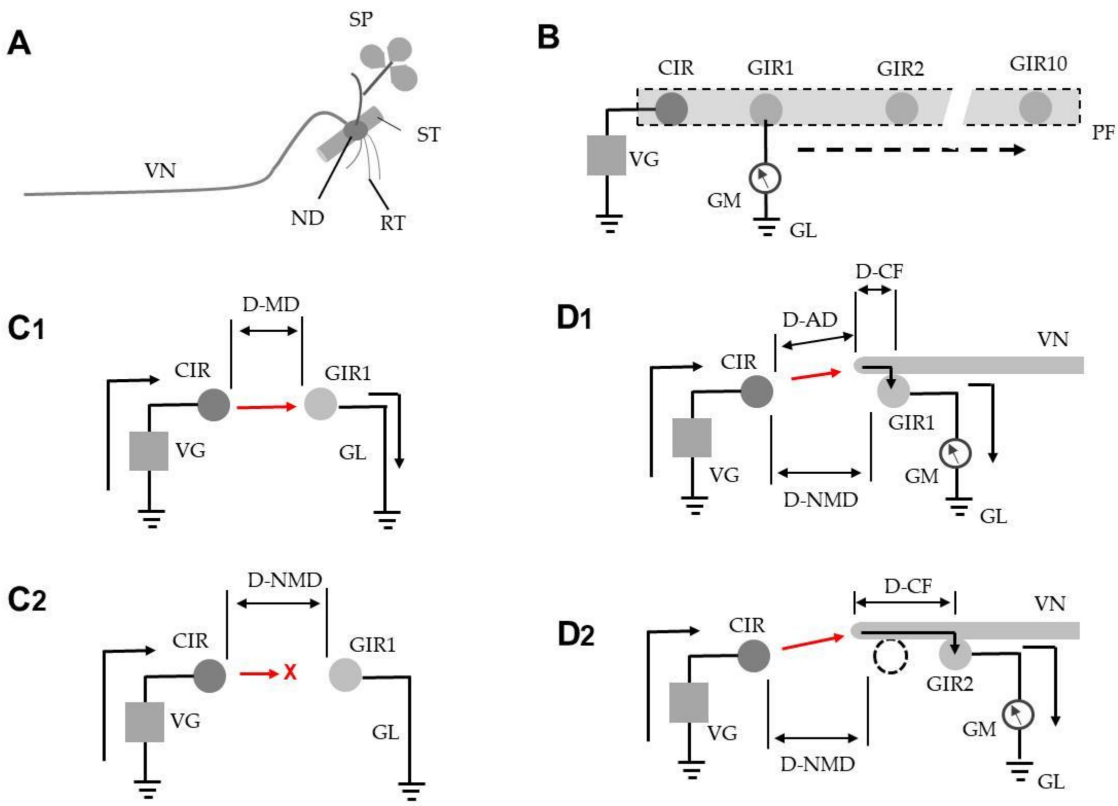

Figure 1. (**A**) Vine development from the node of a stem cut from a kudzu plant. (**B**) Structure of the ladder-shaped exposer of the pulsed arc discharge (LE-PAD, cross-sectional view). Determination of the arc discharge distance required to cause mechanical discharge (**C1**) and the non-mechanical discharge-causing distance (**C2**) between the charged iron rod (CIR) and Grounded iron rod (GIR1). Exposure of a vine in contact with GIR1 (**D1**) and GIR2 (**D2**) to the arc discharge. The solid arrow represents the direction of electricity movement with the arc discharge (red arrow), and the dotted arrow shows the change in the GIRs connected to the grounded line. Abbreviations: VN, vine (runner). ND, node. SP, sapling. RT, root. ST, stem cutting. VG, voltage generator. CIR, negatively charged iron rod. GIR1–GIR10, grounded iron rods 1–10. GL, grounded line. PF, polypropylene frame. GM, galvanometer. D-MD, distance to cause mechanical discharge. D-NMD, distance to cause no mechanical discharge. D-AD, distance to cause arc discharge. D-CF, distance of current flow on the vine.

2.2. Measurement of the Conductivity of Kudzu Vines

In the first experiment, undetached vines developed from the saplings mentioned above were examined for their conductivity with a digital surface resistance meter (Satotech, Kanagawa, Japan). Two points (the apical tip and designated stem point) of the vine were touched with the electrodes of the resistance meter (point-to-point resistance measurement), and the conductivity (S/m) was calculated from the resistance values obtained.

In the second experiment, we examined the relationship between electrical conductivity and evaporation of body water in the vine. We measured body water content using the loss-on-drying (LOD) method [32]. The vine was cut at a point 50 cm from the apex, weighed, and then placed in a thermostat-controlled convection oven set to 35 °C. Once a constant weight was attained, the difference between the initial and final weights was calculated to determine the amount of moisture (body water) vaporised. Vines that had lost different percentages of body water according to the weight loss curve obtained from the LOD were collected at different durations of desiccation and examined for their electrical conductivity using the method mentioned above. Data are expressed as the magnitude of the electric current, which was calculated from the resistance value.

2.3. Construction of the Ladder-Shaped Exposer of the Pulsed Arc Discharge (LE-PAD) and an Assay of Arc Discharge Generation

Figure 1B shows the configuration of the LE-PAD, which consisted of 11 identical iron rods (6-mm diameter, 30 cm length) arrayed in parallel and fixed with a polypropylene frame (insulator) and a direct current voltage generator (pulse-charging type, 1-minute pulse interval, −10 kV usable voltage, Suematsu Denshi, Kumamoto, Japan). Ten grounded iron rods (GIR1–GIR10) were arranged in parallel at 50-mm intervals, and a grounded line was linked to one or all of the GIRs.

In the first experiment, the interval between the negatively charged iron rod (CIR) and GIR1 was changed and charged with a voltage of −10 kV to determine the distance at which a mechanical discharge (arc discharge) occurred between them. In the subsequent experiment, the distance was fixed at 15 mm (the randomly selected distance at which there was no mechanical discharge, Figure 1C1,C2).

In the second experiment, an undetached vine of a kudzu sapling was placed on the LE-PAD and brought close to the CIR in a stepwise manner, then charged with a voltage of −10 kV to determine the distance from the CIR at which an arc discharge is created to the vine tip. In the subsequent arc discharge exposure experiments, we positioned the vine tip at specified sites (5, 7, and 9 mm from the CIR) and changed the GIR linked to the grounded line (Figure 1D1,D2). The exposures of the vines to the arc discharge were video-recorded. The electric current was recorded with a galvanometer (Sanwa Electric Instrument, Tokyo, Japan) integrated into the grounded line, and its magnitude was measured with a current detector (detection range, 0.01 μA to 10 A) integrated into the galvanometer. Simultaneously, the sound produced by the arc discharge was measured in decibels with a sound-level meter (Sato Tech, Kanagawa, Japan). The sound profile was recorded with a spectrum analyser integrated into the sound-level meter. We photographed discharge-exposed vines with a thermographic camera (Flir One, FLIR Systems, Wilsonville, OR, USA) to compare heat-zone images among discharge-exposed and nonexposed samples. The temperature of the apical areas of the vine was determined with the multiple spot temperature meters for selectable onscreen temperature tracking regions in the camera. The subsequent growth of discharge-exposed vines was recorded for one week to determine the degree of wounding of the vine apical regions. Damage was assessed by wilting and/or drying of the electrified region of the vine.

2.4. A Simplified Version of the LE-PAD (SE-PAD) for Practical Use

We fabricated an SE-PAD for practical use from copper or aluminium wires and a ready-made polypropylene net (insulator, Figure 2A). Four metal wires (2 mm diameter, 30–100 cm length) were attached to a net in parallel and at specific intervals (50 mm). One wire at the highest position was linked to a solar cell-driven pulse-type voltage generator (Suematsu Denshi), which is commonly used in electric fences to repel wild animals from crop fields, and charged with a voltage of −10 kV at a 1-s interval. The remaining three wires were linked to a grounded line.

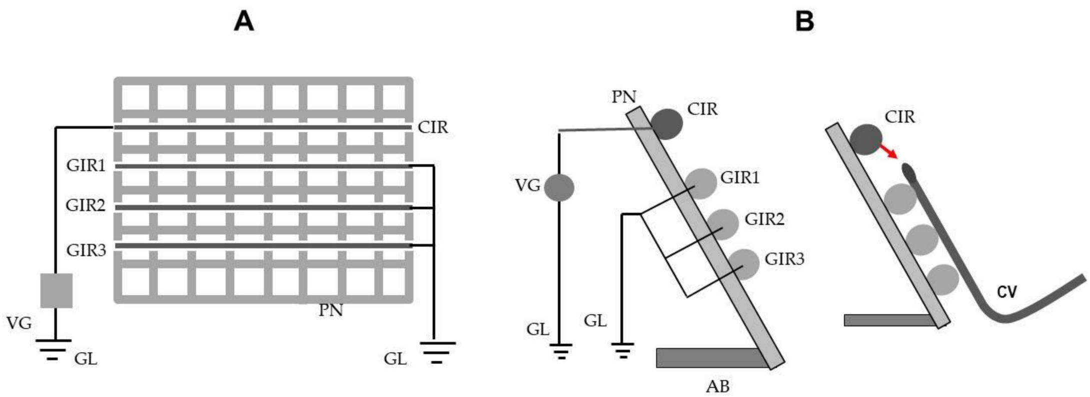

Figure 2. A simplified pulsed arc discharge exposer (SE-PAD) for practical use. (**A**) Structure of the SE-PAD in which four copper or aluminium wires were attached to a polypropylene net (PN). One wire (charged iron rod [CIR]) was linked to a voltage generator (VG), and the remaining three wires (grounded iron rods [GIR1–GIR3]) were linked to a grounded line (GL). (**B**) The SE-PAD attached to a flat aluminium board (AB) to control vines (CV) creeping along the ground and climbing along the ladders of the SE-PAD. The red arrow represents the arc discharge from the CIR.

In the first experiment, the SE-PAD was attached to a fence to control the vines that were climbing along it. This experiment lasted for one month.

In the second experiment, to control vines creeping along the ground, we attached an SE-PAD (15 cm height, 100-cm length) to a flat aluminium board (40-mm width, 100-cm length) with a slope of 95–100° (Figure 2B). A block of land was partitioned into squares together with the boards and with the inclined SE-PAD. This apparatus was set at 20 sites, and the functionality was surveyed over three months (June to August, the most suitable periods for kudzu vine growth). Figure S1 shows photographs of the apparatus.

2.5. Statistical Analysis

All experiments were repeated five times, and data are presented as means and standard deviations. Analyses were performed to identify significant differences among conditions as well as correlations between factors, as shown in the figure and table legends.

3. Results and Discussion

3.1. The Conductive Nature of the Kudzu Vine is Essential for the Arc Discharge Exposure Treatment

The purpose of this study was to expose the apical region of the kudzu vine to an arc discharge to impede its subsequent growth. The conductive nature of the kudzu vine was a prerequisite for receiving electricity from the charged conductor and discharging it to the ground via a GIR. The apparatus designed in this study produced an electric circuit. Electricity was pumped upward from a grounded conductor by the voltage produced by a voltage generator. It then accumulated on the surface of the iron rod connected to the voltage generator and was sent back to the grounded conductor through the vines of the plant. However, the release of electricity from the charged conductor was impeded by the air between the conductor and the plant. Therefore, a relatively high force (i.e., a high potential difference) was needed to break down the resistance of the air (i.e., dielectric breakdown of gases) to successfully transfer the electricity [30]. This could be achieved by applying a high voltage to the iron rod and/or reducing the distance between the charged rod and the plant. The conductivity of the kudzu vine was an additional impediment to current flow. In the study, the voltage used for the arc discharge exposure was fixed (−10 kV), and, therefore, we focused on the conductivity of kudzu vines and, then, the distances between the charged conductor and the vine apical tip (arc discharge distance) and between the apical tip and designated position of the vine stem (current flow distance).

In the first experiment, we measured the electrical conductivity of the vine by a point-to-point resistance measurement. The electrical conductivity of the vine was defined as the density of the vine's electrical conductivity based on the potential difference produced between points that were touched. Figure 3A shows the change in resistance of a kudzu vine when the point-to-point distance for current flow was changed. As the distance became longer, the resistance became larger. There was a linear relationship between the increase in the current flow distance and electrical resistance. The conductivity of the kudzu vine was calculated to be approximately 10^{-5} S/m. It appeared that the vine was a suitable conductor for an electric discharge exposure treatment. Nevertheless, the electric current that flowed on the kudzu vine decreased in direct proportion to the increase in distance. This implies that electricity could be transmitted through a limited region from the vine apex.

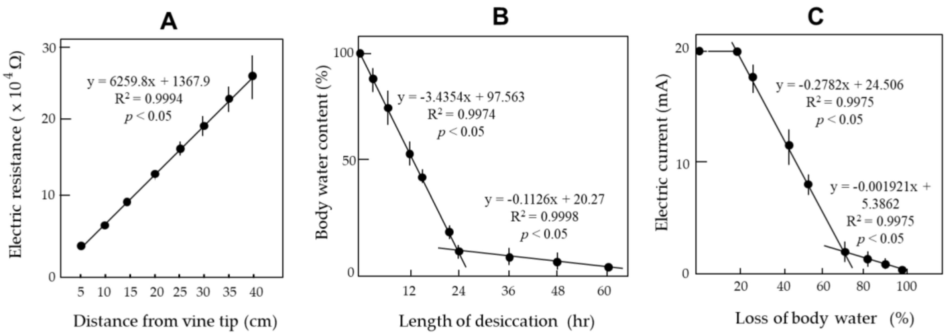

Figure 3. (**A**) The relationship between electrical resistance and the distance from the apical tip to the designated point of a kudzu vine. (**B**) The relationship between the duration of desiccation and the loss of body water in kudzu vines by the loss-on-drying (LOD) method. (**C**) Change in the electrical conductivity of vine samples with different degrees of water loss. Resistance was measured with a point-to-point resistance measurement. Twenty vines were used for each distance including each duration of desiccation, and each degree of water loss. The means and standard deviations were calculated from five replicates of the experiments. Vertical line on each dot represents standard deviation. Two regression lines are shown in each figure.

Figure 3B shows the temporal change in body weight of the test vines. The technique used in this study effectively dehydrated the vines to a desired level by changing the duration of desiccation. The data exhibited a high degree of reproducibility. There were two distinct phases in the loss of body water: an initial rapid loss and then a slower phase. In both phases, a linear relationship was observed between the duration of body desiccation and the extent of body water loss. The total water content constituted 85–90% of the body weight. Water may also become locked in molecular structures as bound moisture with the result that greater amounts of heat energy are needed to release the tightly bound moisture. The LOD treatment likely promoted the vaporisation of free water in the plant body.

Using this method, we collected vine samples with different degrees of water loss and examined their electrical conductivity. We found that conductivity did not change until 80% of the water content had been vaporised, and then it decreased substantially at greater degrees of water loss (Figure 3C). These results indicate that, for our technique to be effective, water loss from the vine should be maintained at less than 85% of total water to ensure sufficient electrical conductivity of the vine.

3.2. Exposing a Kudzu Vine to an Arc Discharge Can Destroy the Apical Growing Point of the Vine, Inhibiting Its Subsequent Growth

Discharge is defined as the generation of an electric current between opposite poles due to the dielectric breakdown of gases in the electric field, according to the potential difference between the opposite poles [30]. If the grounded conductor is one of the poles (i.e., the recipient of electricity), the discharge occurs more easily because this conductor receives electricity without any restriction (in this experiment, 10 mA of the maximum current of the voltage generator). In an electric field, a corona discharge occurs first, which then changes from a glow discharge (or surface discharge) to a brush-like discharge as the applied voltage increases and/or the distance between the poles decreases. The discharge breaks down with the occurrence of an arc discharge between the two poles [33]. Plants are conductive, and, therefore, when they receive electricity resulting from the discharge of a charged conductor, an electric current flows through their bodies [29]. If a continuous voltage is applied to the conductor, a continuous discharge from the charged conductor occurs. A continuous arc discharge can produce a continuous electric current that causes damage to targets due to heating, based on the Joule effect [34]. In addition, it produces a strong force that can destroy small organisms through a high-voltage-mediated transient electric current flow [35–37]. Our preliminary investigation indicated that, in the LE-PAD, the pulsed arc discharge from the charged conductor was generated when the apical tip of the vine reached the test position of 9 mm from the charged conductor. The focus of the present experiment was to clarify whether the pulsed voltage caused damage to the vines.

When the arc discharge occurred between the charged conductor and the vine placed on the LE-PAD, electricity moved through the ground-to-ground circuit that included the air and plant body (Figure 1D1,D2). The focus of the experiment was to examine the effects of changes in the arc discharge distance (D-AD) and the distance of current flow on the vine (D-CF in Figure 1D1,D2) on the generation of current flow and arc discharge sound in order to verify the inhibitory effects of arc discharge exposure. The arc discharge sound was a sonic boom caused by the shock wave from the high-speed electrons moving in the electric field, and its intensity was an indicator of the impact strength of the shock wave produced by the arc discharge exposure.

Figure 4A shows the kudzu vine exposed to an arc discharge from the CIR. Figure S2 shows the magnitude of the electric current that flowed through the vine following the arc discharge exposure (A), the intensity (B), and the number of arc discharge sounds (C in Figure S2). With the application of a pulsed voltage, the electric current and arc discharge sound were generated simultaneously as the voltage was pulsed. As D-AD became longer, the current magnitude and sound intensity became lower, and the number of arc discharge sounds increased. Eventually, the vines were wounded by the arc discharge exposure treatment. Figure 4B,C show the electrified region of the arc discharge–exposed vines. It appeared that water was not supplied to this region after it was exposed to the arc discharge. It is likely that the exposure destroyed the vein system and prevented water movement in this region. More importantly, the electric current and arc discharge sound stopped automatically, likely because of the lower conductivity of the electrified vine region. We believe that the electrified region was heated by the current flow through the arc discharge exposure to cause the rapid vaporisation of the plant body water. Figure 4D–F show thermographic data, indicating that the temperature of the electrified region was increased by a repeated pulsed arc discharge exposure. It is likely that this increase in temperature (75–80 °C) caused water vaporisation in the plant body, which led to lower conductivity. As D-AD or D-CF became longer, the number of arc discharge sounds (i.e., the duration of the pulsed arc discharge exposure) increased and sufficient damage was caused to the vine. In future studies, light and electron microscopic analyses of the discharge-exposed vine will be conducted to determine the arc discharge–mediated plant disintegration mechanism.

Table 1 shows an inhibitory function of the LE-PAD under different D-AD and D-CF conditions. In all D-AD distances, the inhibitory function became weaker as the more distant GIR was linked to a grounded line (i.e., the path of current flow on the vine became longer) due to the increase in the electric resistance. At 5 mm of the D-AD, all of the discharge-exposed vines were prevented from elongating even when the GIR8 was grounded (approximately 37 cm from the vein apex). As the D-AD became longer (7 and 9 mm), the D-CF became shorter (approximately 32 and 26 cm from the apex, respectively). In fact, 100% elongation inhibition at 7 and 9 mm of the D-AD was detected when the GIR7 and 6 were grounded, respectively. Therefore, the present result indicated that, if we link the grounded line to the GIR6, all vines could be inhibited regardless of the D-AD. In a real situation, the creeping vine is subjected to the arc discharge exposure when it reached 9 mm from the CIR.

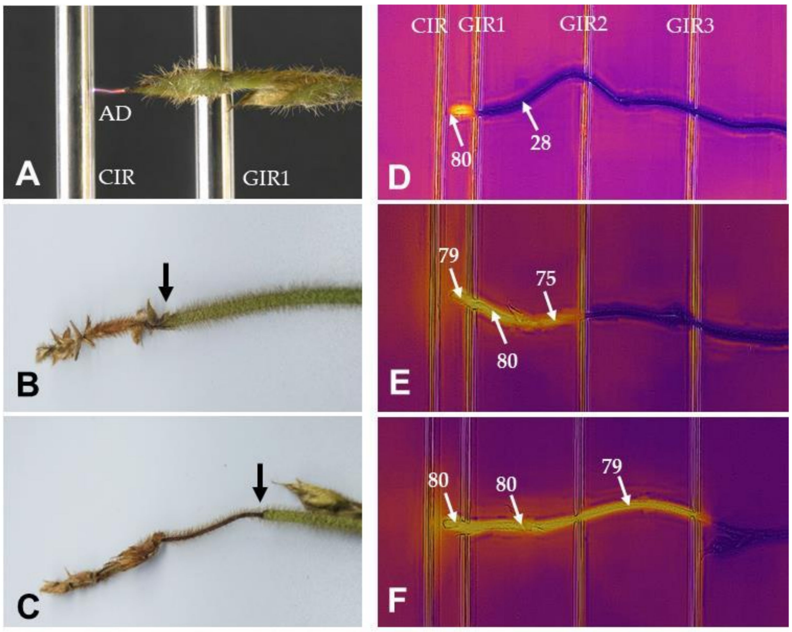

Figure 4. (**A**) Exposure of a kudzu vine, which was contacted with a ground iron rod (GIR1), to a pulsed arc discharge (AD) from a negatively charged ion rod (CIR). (**B**, **C**) Arc discharge-exposed vines showing the dryness of the electrified region (five days after the arc discharge exposure treatment). The arrows in B and C show the points of the vines that came into contact with the second and third grounded iron rods (GIR2 and GIR3), respectively. (**D**–**F**) Thermographic demonstration of the increase in temperature in a kudzu vine exposed to a pulsed arc discharge at −10 kV. In **D**, **E**, and **F**, GIR1, 2 and 3 were linked to a grounded line, respectively. Subfigures **D**–**F** represent temperature (°C) measured with a spot temperature meter of a camera. The arrow was the site of a temperature measurement. The interval between CIR and vine apex was fixed at 5 mm.

Table 1. Percentage of damaged *Pueraria montana* var. *lobata* vines subjected to an arc discharge from a charged iron rod (CIR) of the ladder-shaped arc discharge exposer (LE-PAD) [a].

GIR Linked to a Grounded Line [b]	Interval (mm) between CIR and Vine Apex		
	5	7	9
1	100 [x]	100 [x]	100 [x]
2	100 [x]	100 [x]	100 [x]
3	100 [x]	100 [x]	100 [x]
4	100 [x]	100 [x]	100 [x]
5	100 [x]	100 [x]	100 [x]
6	100 [x]	100 [x]	100 [x]
7	100 [x]	100 [x]	89.0 ± 4.2 [y]
8	100 [x]	92.0 ± 4.5 [y]	82.0 ± 4.5 [y]
9	92.0 ± 2.7 [y]	91.0 ± 4.2 [y]	47.0 ± 5.7 [z]
10	89.0 ± 4.2 [y]	69.0 ± 6.5 [z]	36.0 ± 7.4 [z]

[a] Assessed five days after the discharge exposure treatment. [b] The vine was placed on grounded iron rods (GIR1–GIR10) of the LE-PAD to create different intervals between the CIR and vine apex, and one of the GIRs was linked to a grounded line. Twenty vines were used for each GIR, and means and standard deviations were calculated from five experimental replicates. Letters (x–z) for the means in each vertical column indicate significant differences ($p < 0.05$), according to Tukey's test.

Based on the results obtained in the present study, we constructed a simple version (SE-PAD) of the LE-PAD (Figure 2), where one CIR and three GIRs were paralleled at an interval of 10 cm. The CIR was linked to a pulse-type voltage generator, and three GIRs were linked to a grounded line. In this apparatus, the vine apex was subjected to arc discharge at a 9-mm position from the CIR, and the 10-cm apex of the vine could be destroyed. Simultaneous grounding of three GIRs was useful to ground the creeping vine securely.

3.3. The SE-PAD is a Promising Tool for Impeding the Invasive Growth of Creeping Kudzu Vines

The first requirement for practical use was to confirm the ability of the SE-PAD to inhibit vine elongation by kudzu. For this purpose, we hung the SE-PAD on a fence and examined its ability to inhibit the growth of vines climbing along the fence (Figure 5A). In all tests, the SE-PAD was functional with the arc discharge exposure damaging the vines to the extent that their invasive growth was impeded. The drying up of their apical region resulted in their elongation ceasing. Figure 5A (lower photograph) shows two vines concurrently approaching the CIR. In theory, the nearest target (the right vine in the photograph) was preferentially exposed to the arc discharge until the discharge stopped automatically. Another vine was allowed to grow continuously and was subjected to a stronger arc discharge after the first discharge stopped because the distance between the second vine and the CIR was shortened. In this manner, the invasive growth of all vines approaching the CIR could be prevented.

Figure 5. (**A**) A simplified pulsed arc discharge exposer (SE-PAD) attached to a fence with kudzu plants placed nearby to test its ability (upper), and fence-climbing vines whose apical tips were damaged by arc discharge exposure (lower). (**B**) An SE-PAD-protected plot of land (upper) and an unprotected plot (uncharged SE-PAD) as a control (lower) three months after the apparatus was set up.

The results of the study indicated the feasibility of the SE-PAD, and, therefore, it was used to control vines creeping along the ground. To achieve this, we used an inclined SE-PAD attached to a flat board (Figure 2B and Figure S1B) to prevent the creeping vines from entering a square block of land. The creeping vine climbed the ladders (GIR1–GIR3) along the slope of the inclined SE-PAD and then received an electric current through the arc discharge from the CIR when its apex got close to the CIR (Figure 2B). To ensure exposure to the electric discharge, it was essential that the vine body was exactly grounded (i.e., in contact with the GIR[s]). The incline was effective because it enabled the vine's weight to create close contact between the grounded ladder and the vine. Figure 5B (upper photograph) shows that the apparatus was extremely effective at preventing the entry of the creeping vines into the guarded area of land. Complete prevention of all vine growth was attained in all sites tested. These results indicate that the SE-PAD could be a promising physical tool for impeding the invasive growth of kudzu vines.

The effects of rainfall on the conductivity of the vine are important with regard to the functionality of the SE-PAD. Because rain-wet vines become more conductive, they were subjected to an arc discharge with a larger electric current and stronger sound. The vines were, therefore, more extensively damaged by the arc discharge exposure on rainy days (data not shown). The rainfall caused no mechanical damage to the SE-PAD.

It is interesting that there was a clear difference in conductivity between young slender vines and older thick vines. Both types of vine were impeded by the present discharge exposure treatment, but it appeared that the older vines received larger amounts of electricity and exhibited more severe damage than the young slender vines (data not shown). Although we obtained no data to verify this difference, further investigation will be undertaken to clarify the change in bioelectric properties associated with vine growth and differentiation.

The framework of the apparatus is simple and easy to fabricate from materials that are widely available. In addition, the voltage generator of an electric fence is suitable for use in the system. Electric fences are ubiquitous and essential in modern agriculture. Accidents in association with agricultural electric fences are very rare [38]. Although unintentional human contact with electric fences occurs regularly, it causes little more than temporary discomfort [38]. In the present system, which targets both wild animals and creeping vines, it is possible that wild animals may come into contact with an electric wire on the fence while a vine is being exposed to the arc discharge. In this case, the discharge generation will move to the animal. However, because the animal will immediately move away, the discharge point will return to the original vine. Thus, the use of a pulse-type voltage generator is an effective and economical approach for preventing both wild animals and weeds from invading crop fields.

4. Conclusions

An electric field-based phenomenon was effective when used in a unique weed control application. In this study, a creeping plant (kudzu) invading a crop field was targeted for eradication by means of a non-agrochemical method during organic farming. The electrostatic phenomenon used for weed control was an electric discharge in a dynamic electric field, to which creeping kudzu vines were exposed in an attempt to destroy the growing point at the apical end. The discharge exposure was sufficiently effective that the targets were destroyed immediately. This apparatus remained functional during long-term operation under field conditions. Thus, we developed a practical physical method of controlling weeds invading an agricultural field, which could be useful for organic farmers.

Supplementary Materials: The following are available online at http://www.mdpi.com/2077-0472/10/12/600/s1. Figure S1: A simplified pulsed arc discharge exposure (SE-PAD) and a solar cell–driven pulse-type voltage generator, Figure S2: Effects of change in D-AD on the generation of an electric current on a vine (A), and the intensity (B) and frequency (C) of the arc discharge sound.

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