Int. J. Biometeor. 1981, vol. 25, number 4, pp. 309-321.

Electroculture for Crop Enhancement by Air Anions

by

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ABSTRACT. — Electroculture, the practice of applying strong electric fields or other sources of small air ions to growing plants, has potential to markedly increase crop production and to speed crop growth. The considerable evidence for its effectiveness, and the studies of the mechanisms for its actions are discussed. A mild current of air anions ($4\,pA/cm^2$) stimulates bean crop growth and also earlier blossoming and increased growth in the annual, *Exacum affine* (Persian violet), as well as in seedling geraniums. The present results would indicate that the growing period required until the plants reach a saleable stage of maturity can be shortened by about two weeks under greenhouse conditions.

REVIEW OF PAST RESEARCH

The use of electricity to affect the growth of plants, although it has had a somewhat stormy history in the earlier decades of this century, has through the elegant research of Krueger, Bachman, Murr, and many others, become established as having much promise for the practical realization of increasing crop harvests.

There have been many studies on the effects caused by electrical currents in plants, and certain of the functional responses are by now well established. That electrical currents might influence vegetation was early suggested and attempted by Giambatissta Beccaria (1775) of the University of Turin in 1775. His suggestion was actively explored by Bertholon (1783), Gardini (1784), Ingenhausz (1788), Grandeau (1878), and Sturgeon (1846). Lemström (1904) observed that an electrical discharge from needle points placed above cereal seedlings produced a detectable growth stimulation. His results were confirmed by Gassner (1907).

Since that time, a spate of papers have appeared. Blackman, Legg and Gregory (1923) and Blackman (1924) conducted a carefully controlled study of the growth of the coleoptile of barley seedlings and concluded that a maximum effect in enhancing growth occurred when a current of about 50×10^{-12} A (50 pA) per plant was passed. An aftereffect was also noted, in that an increase in growth rate persisted for several hours after cessation of the current. These experiments were followed by pot culture and field tests with wheat, barley and corn. Successes and some failures were carefully reported, with successes considerably outnumbering the failures. In outdoor pot culture experiments, barley yield increased $18 \pm 2.4\%$, and corn increased $27 \pm 5.8\%$. In field experiments using thin wires carrying 40 to 80 kV strung 2,1 m above soil level, 14 trials gave positive yield increases for barley, oats, and

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Received 23 August 1980.

wheat, while 4 were negative. Eleven showed increases greater than 10% and nine were greater than 30%.

Agreement as to the beneficial effects of applied electrical fields to crop growth, however, has not been unanimous. Collins, Flint and McLane (1929) spent several years during the 1920's in laboratory studies on barley and corn seedlings and could detect no appreciable increase in growth due to electric fields. Likewise, Briggs (1938) and Briggs et al. (1926), obtained essentially negative results on greenhouse and field studies with carefully controlled experiments. Persistence by more recent workers despite the ups and downs experienced in these very early days has, however, led to a recent large body of convincing evidence that not only does electroculture provide either increased or decreased crop yield at will, but that the fundamental causes are becoming known. This has been at least partly due to the increased sophistication of modern research methods.

Krueger, Kotaka and Andriese (1964) and Krueger et al. (1978) have shown that air ions are the principal mediating agent in electroculture. In particular, iron stress, especially associated with that readily soluble in 1 *N* HCl, is critical to the growth and to the onset of chlorosis during the presence of applied electric fields. Murr (1964, 1965a, b) showed that although nitrogen or phosphorus levels were hardly affected, applied fields did bring about major changes in several trace element levels, such as Fe, Zn, and Al. He suggested that since these elements are key constituents of certain enzymes in the oxidative pathways, that the relatively large effect by air ions focuses on the controls to these pathways. Kotaka and Krueger (1967) were able to readily detect significant biological changes induced by applied electrical fields or by the direct administration of air ions.

Among these changes, in addition to that noted on Fe levels, were alterations in the increased production of cytochrome c and the acceleration of oxygen consumption. Alterations in the distribution of growth control substances were observed by Clark (1937). Smith and Fuller (1961) noted that the release of indole acetic acid paralleled the effect of positive ions. Went (1932) had earlier hypothesized that electrical fields were active in bringing about redistributions of auxins. From this brief discussion of some of the highlights of more important variables in the successful application of electroculture to higher plants, we now turn to a brief summary of the more recent research, looking in particular at the growth accelerating and retarding effects found by various research groups.

REVIEW OF RECENT RESEARCH

Research on electroculture of plants during the period following World War II has, as noted above, established that applied electric fields can accelerate or inhibit the growth of higher plants. Moreover, some of the basic processes responsible have been pin-pointed. Nyrop (1946) examined the killing effects of applied electric fields on bacteria and on foot-and-mouth virus. Smith and Fuller (1961) indicated that positive air ions, especially CO_2^+, accelerated plant growth in the blue-green alga, *Microcoleus vaginatus,* by releasing indole acetic acid. Krueger, Kotaka and Andriese (1962) examined the effect of added positive and negative air ions on the growth of oat seedlings (*Avena sativa*), and showed that ions of either sign could accelerate growth. In a subsequent paper, Krueger, Kotaka and Andriese (1963) they showed similar results for oats and for barley (*Hordeum vulgare*), and found that an increase of 30% to 60% in dry weight could be obtained. An encapsulated tritium source was used to supply ions in various gases supplied, and the dominance of ion charge was controlled by passing the effluent gases over appropriately charged grids. Ion densities in the plant growth chambers was about 10^{-13} A plant. Krueger, Kotaka and Andriese (1963) observed effects of the electric field upon the iron, cytochrome c and chlorophyll levels in barley. Although Smith and Fuller (1961) had suggested that the applied fields were affecting the indole acetic acid levels, Krueger, Kotaka and Andriese (1963) found no significant shift in the free or bound levels of IAA in barley seedlings, but substantiated their air ion results. Krueger, Kotaka and Andriese (1964) using their tritium-source ion generator, showed that O_2^- or O_2^+ stimulated the production of cytochrome c and of Fe-containing enzymes. The role of $CO_2^{\pm}$ was not explained, and still remains a mystery. The role of Fe as affected by air ions was much clarified by their finding that there are three types of iron in young seedlings; (1) Constitutional Fe, destined for cytochromes and other Fe-containing enzymes, and which is not extractable by 1 *N* HCl from mascerated plants; (2) Fe destined for chlorophyll synthesis in the first and second leaves. This iron is extractable by 1 *N* HCl; (3) Free-state iron (easily soluble).

They suggest that the air ions in some way enhance or guide the synthesis of cytochrome c and other Fe-containing enzymes. It is suggested that the distribution of the iron among the various metabolic pathways is then affected by ions of either charge, by the action of the ions upon certain "governors" of the iron distribution pathways in the mitochondria and chloroplasts. These as yet unknown "pathway governors" are then the site of the more important actions of air ions upon growth pattern.

Pratt (1962) on working with black mustard seedlings (*Brassica nigra*) observed that air ions of either sign when produced at a rate of 9.5×10^6 ions/(ml·s) in the air above the seedlings caused delay in the emergence of shoots in these seedlings, but also noticed that by the fifth day an acceleration in shoot length occurred compared to that of the controls. Murr (1963) observed tip damage to orchard grass seedlings by applied electric fields, and at first suggested that a possible mechanism to explain the effects would be an ionization phenomenon involving the migration of polarized salts which initiated cell bursting by catastrophic osmosis. He later (Murr, 1964) concluded that this mechanism was incorrect, and that the mechanism was more properly one concerned with biochemical transformations involving enzyme constituents of cell metabolism. Spectroscopic and micro-Kjeldahl analyses of the leaf tips showed that the elemental N and P contents were rather little affected, but that the levels of the trace elements, Fe, Zn, and Al were demonstrably affected. It seemed reasonable then to ascribe the effects of the applied field to mechanisms involving the metallo-enzymes. Further studies (Murr 1965a, b, 1966a, b) on orchard grass and grain sorghum showed that Ca, Mg, and Mn levels were also affected by applied fields. The weight-response curves obtained by Murr (1966b) for sweet corn (Pennlewis) as affected by various intensities of the applied electric field reversed at 100 kV/m and for yellow bush bean at 60 kV/m (Murr, 1965b, 1966a) showed yield increases of up to 30%. There is a rather wide region of field strengths for which the weight gain is positive, but above this region of field intensities (circa 1 kV/cm), the plant is inhibited in its growth. Interestingly, Murr (1966c) showed that plants grown in very low magnetostatic fields were also stimulated. Krueger, Kotaka and Andriese (1965) showed that air ion depletion to lower than normal levels resulted in lowered growth rates.

Anderson and Vad (1965) demonstrated the inhibition of bacterial growth by the application of fields of approximately 3 kV/cm (*Serratia marcescens* and *E. coli*). Sidaway (1966) reported on observing lettuce seed germination (*Lactuca sativa*) that the sign of the applied field made a difference in the growth response and that with a positive electrode above the seed a slight inhibition occurred. (His tabulated results appear to show the opposite) Sidaway and Aspray (1968) found that electrostatic fields had measurable effects upon the respiration of *Arum maculatum, Triticum vulgare, Vicia fabia, Castanea sativa,* and *Ulmus glabra.* Sharp (1967) found a strong correlation between the concentration of small air ions and the germination rate of the uredospores of *Puccinia striiformis,* the causal agent of stripe rust of wheat. Sale and Hamilton (1967) observed killing effects of strong fields (25 kV/cm) on various bacteria and yeasts, noting that yeasts were more sensitive than bacteria. Bentrup (1968), rather than using electrodes placed in the air above the growing organisms as in most other studies, used an electrochemical gradient produced by electrodes immersed in the culture medium which produced transcellular potential differences of about 1 to 10 mV corresponding to about 0.1 to 1 V/cm in the medium. Their studies with horsetail (*Equisetum*), moss (*Funaria*) and with zygotes of a brown alga (*Fucus*) showed that growth of the cells was oriented towards either the anode or cathode, depending upon the growth stage. Kotaka, Krueger and Andriese (1968) were able to correlate the effect of air ions upon the light-induced swelling and dark-induced shrinking of isolated spinach chloroplasts (*Spinacia oleracea* L.). With the light on, either positive or negative ions induced swelling; but induced shrinking in the dark.

An excellent detailed review and discussion of possible mechanisms concerned with the effect of air ions appeared in a long paper by Kotaka and Krueger (1967). It is interesting to note that Feder and Sullivan (1969) observed that ozone depressed frond multiplication and floral production in duckweed (*Lemma perpusilla* #67-6). The presence of only 0.1 ppm of O_3 reduced frond number by a factor of 6.

Krueger (1969), in commenting on electoculture and related experiments, notes that air ions play a large role, but that other factors such as ozone and nitrogen oxides, humidity, and air pollutants can be expected to affect the results and must be monitored in good experiments. The normal concentration of small air ions in "normal" air is about 10^3 to 5×10^3 ions/ml, but that because of rapid recombination mechanisms, the upper practical limit inducible by external means is about 10^6 ions/ml. That such small concentrations (air contains about 2.7×10^{19} molecules/ml) can markedly affect physiological processes such as the growth of higher plants or of mammals is remarkable, but must now be regarded as factual. The small ions readily unite with nuclei and pollutants in air to form large ions (high mass per charge) which have only relatively small effects on organisms. The dominant positive small ions in air are present as the hydrated froms of H^+, or as the negative ions O_2^-, OH^-, CO_3^- and CO_4^-, with possible contributions of ON^-. The principle ionic reactions, according to Krueger (1969) are:

$$CO_2^+ + O_2^+ \Rightarrow O_2^-$$
$$O_2^+ + H_2O \Rightarrow H^+$$
$$N_2^+ + O_2 \Rightarrow O_2^+$$
$$O_2^- + H_2O \Rightarrow OH^-$$
$$CO_2^- \Rightarrow O^- + CO$$
$$O^- + CO_2 \Rightarrow CO_3^-$$

Stersky, Heldman and Hedrick (1970) used applied fields of 6 to 20 kV/m to kill air-borne *Pseudomonas fragi, Serratia marcescens, Candida lipolytica, Penicillium roqueforti,* and *Bacillus subtilis* and observed 40% to 60% kills. Wheaton, Lovely and Bockhop (1971) found small but positive effects on the germination upon exposing seeds of corn and soybeans to static or 60 Hz fields of 500 to 5 500 V across 3.8 cm air gaps for quite short periods (up to 20 s). Bachman, Hademenos and Underwood (1971) examined the effects of intense fields at the tips of barley, measuring the presence of ozone, air ions, and corona current. Among some thirty varieties of plants examined in their preliminary studies, wax beans were observed to be outstandingly sensitive. When an upper electrode plate at 15 kV positive was maintained at a distance of 5 cm above a planting of wax beans, the wax beans germinated faster, grew taller, and grew heavier, and in all ways maintained a lead over control planting which was not exposed to the applied electric field. Their study focused mainly on the behavior of barley seedlings. Ozone appeared (0.01 ppm) in the air when a critical current of 2×10^{-7} A/plant tip was reached.

Direct insertion of electrodes into tomato plants and application of currents of 3 to 15 μA/plant produced linear increases of growth, according Canadian workers (Black et al., 1971). Kotaka and Krueger (1972) noted an effect of air ions on RNAase activity in green barley leaves (*Hordeum vulgare,* var. Mariout). Development of Fe-chlorosis in barley grown in Fe-free nutrient was seen to be accelerated by air ions of either charge. As the concentration of chlorophyll dropped with the onset of chlorosis, there was a marked rise in the concentration of cytochrome c. When Fe was added to the nutrient solution, typical ion-induced acceleration of growth occurred, accompained by the stimulation of cytochrome c synthesis, but no chlorosis developed, and there was no difference in the concentrations of chlorophyll in exposed and normal plants. As in earlier results, ions of either charge reduce the "active" Fe content of seedlings, but the content of residual Fe increases in cytochrome c and other Fe-containing enzymes. Air ions increased the uptake of exogenous Fe and increased O_2 consumption. Both EDTA and air ions decreased the concentration of RNAase (Krueger, Kotaka and Reed, 1973). A general survey of electropotentials in cells, by Higinbotham (1973) presents views of the normal distribution of electric fields in cells, and how it is affected by applied fields.

Bachman and Reichmans (1973) closely examined tip-burning on barley resulting from the application of high electric fields, finding the damage, D, obeying $D = k(V^2/R)t$, where V is the applied voltage, R is the resistance, t is the time of exposure and k is a constant. In careful experiments with barley, electric fields were found to not only enhance growth for field strengths of less than about 2kV/cm, but that enhancement of growth could be produced by some by-products of the corona occurring above the plants, In the latter case, air moved from above electric field-exposed plants was observed to accelerate growth in plants remote from the electrical exposure. Recent summaries of electroculture studies were presented by Krueger and Reed (1976).

EXPERIMENTAL IONOCULTURE RESULTS

In this section is briefly described some of our preliminary experimentation with green bush beans, with Persian violets (*Exacum affine*), and with seedling geraniums. We shall here demonstrate that electroculture (more properly ionoculture, since it is the air ions which prove to be the basic means by which such green plant effects arise) can be an attractive method for horticulturists to use in enhancing throughput in greenhouse operation.

BEAN CROP ENHANCEMENT

Preliminary greenhouse experiments on electroculture (R. Winton et al. unpublished) were done with 60-plant plots of green bush beans (*Phaseolus vulgaris,* cultivar, Provider), planted in clay pots containing 1:1:1 soil, perlite, and peat moss mix. The pots were set out on a wetted blanket atop a metallic screen serving as a grounding connection. Watering was normal exept on the 20th day when 300 ppm of K^+, NO_3^-, and PO_4^{3+} (Peters 20-20-20) was used, and on the 24th and 32nd days when 250 ml per pot of Fe chelate solution (28 g Fe per 80 liters) was added. An increase of 61% and 85% in crop fresh weight by DC and by AC (60 Hz) respectively over the controls was observed at harvest (60 days total). (Plot-to-plot variation was known to be 10 to 20% in this greenhouse.) Electrode height, with 12 kV applied was adjusted (at about 80 cm above plant tips) to maintain a relatively constant DC current density of 7 to 20 pA/plant, from seedplanting to harvest. 6 kV rms was simultaneously suppied to the AC electrode adjusted to the same height. In view of the known Fe-stress evokable by electroculture, the plants were given supplemental Fe chelate (0.1 g/plant) during the 3rd and 4th weeks. The positive results obtained here confirm the earlier observations of Murr (1965a, b) and of Bachman, Hademanos and Underwood (1971) and suggest the desirability of trace element metal supplement during electroculture.

ACCELERATION OF BLOSSOMING IN PERSIAN VIOLETS

The objectives of the present study have been to explore the possibility that commercially desirable plants might be favorably affected by mild air ion treatments, while under commercially realistic conditions. Our previous studies using grids of fine wire above the plants, although successful in indicating the enhancement of growth, fruiting, and crop size, were hampered by the complexity and mechanical delicacy of the electrode system. The present study was examined the use of small needles recessed in plastic cavities, and supplied by heavily insulated wires, to see if increased safety and simplifying convenience could be obtained along with the beneficial effects of the air ions from such sources. We might anticipate the conclusions by saying that the results have been very satisfying.

EXPERIMENTAL ASPECTS:

Since Krueger et al. (1978) have shown that it is primarily the air ions and not the presence of an electric field per se which is mainly responsible for the enhancement of plant growth during "electroculture" experiments, we have therefore sought to emphasize this factor during our studies. To this end, we used charged-needle emitters purchased from Santek

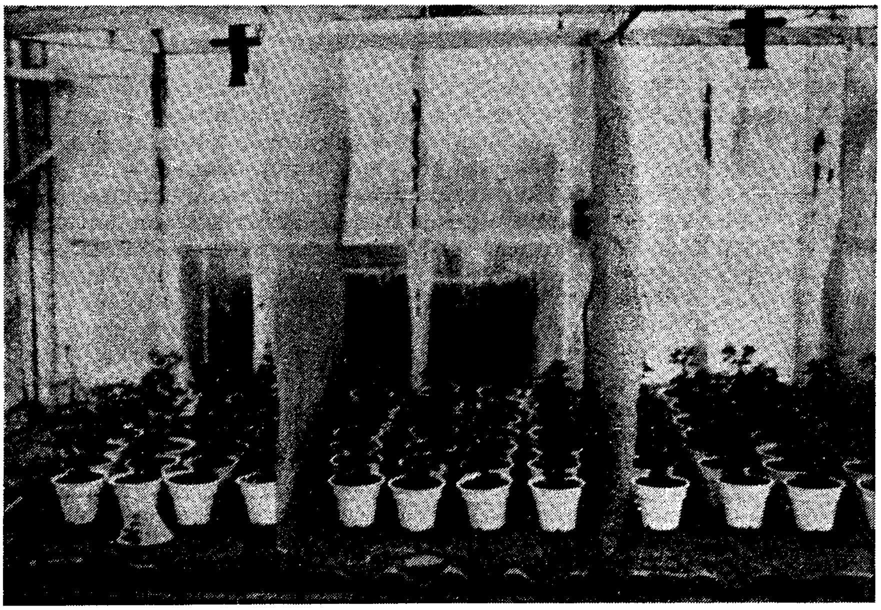

Fig. 1. Remote view showing bays 1, 2, 3, 5, 6, 7 and ion supply (emitter) heads as black objects above the *Exacum affine*, var. petite. Note wire mesh (grounded) isolating the bays from each other.

Fig. 2. Comparison of *Exacum affine*, var. petite, growing as the control (shown on left) and exposed to air anions (on right) as of the 31st day of treatment.

Inc. (4095 N. 28th Way, Hollywood, FL, 33020) and powered by their unipolar negative ion generator, model 331.

The 196 plants, as 65 mm average height seedlings, were set out in seven sets of 28. Four sets had air anions supplied from the ion emitters above them, while three sets served as controls. The 196 plants stood in seven screened bays along a 4.2 m table in the greenhouse, with 8 mm hardware cloth (galvanized iron) along sides of each bay. The electrically grounded wire mesh extended up from the table 100 cm to the height of the ion emitters which hung in the center of the four activated bays. The activated bays were set alternate with the control bays. Measurement showed that the air anions did not detectably penetrate from the activated bays into the control bays (current less than 0.01 nA/cm^2). Illumination, watering, fertilizer, and other growing conditions were held closely identical in the bays. Illumination was by natural light. (Figs. 1 and 2).

The plants, seedlings of *Exacum affine cv. petite* of average height about 65 mm were planted in 10 cm diameter vented plastic pots in "mix" soil, and set out as described for the bean experiments, as four rows of seven pots, per bay, on 9 February 1979. On the 18th day they were watered with "Peters" formula fertilizer. On the 22nd day, an application of circa 3 g of Osmocote 14-14-14 fertilizer (slow release) dressing was applied. Blossom counts and plant heights were measured at suitable intervals. The plants were sacrificed on the 61st day to make the biomass measurements.

The anion flux was measured at the tips of the growing plants. The flux was measured using a 100 cm^2 copper disc connected via a shielded lead connected to a sensitive electrometer. The charged-needle emitters were positioned 100 cm above the plant tops, and provided a current of 0.6 nA in the center of the bay and a current of 0.3 nA at the periphery, averaging 0.4 $nA/100 cm^2$. Curing the 55 days of monitoring, this current stayed quite constant, increasing briefly at time to about 0.8 $nA/100 cm^2$ at the central (maximum) sites. Parenthetically, it may be noted that although a single charged needle emitter can normally supply ions to 4 m^2 area, we restricted each to a 0.6 m^2 area here.

During the experimental period, an application of diazinon was made for control of fungus gnats on the 23rd day.

It may be remarked that the presence of the ion emitters provided little or no inconvenience to the personnel. The design of the emitters, with the needle point sitting within a small hemispherical recess of non-conductive plastic reduces the possibility of shock hazard to negligible proportions. The tiny currents available even from direct and deliberate contact with the emitters or their supply wires (about 10 μA) are far less than that normally regarded as dangerous to personnel (about 1000 μA).

RESULTS AND CONCLUSIONS

A marked increase of blossoming rate was noted among the plants exposed to the air anions. This is shown graphically in Fig. 3 and 4. Figure 3 shows the average number of blossoms per plant as a function of the days duration of the ion treatment. Figure 4 shows the percentage of the plants which had reached a commercially acceptable level of blossoming (4 or more blossoms per plant), again as a function of the duration of the ion treatment. At times the anion treated plants averaged 4 to 7 times as many blossoms per plant. This favorable ratio persisted until the control plants began to reach their (slower) maturation.

An increase in the average plant height among the ion treated plants was also evident, as can be observed in Fig. 5.

GROWTH AND BLOSSOMING ENHANCEMENT IN GERANIUMS

In the present study, a set of grids consisting of fine nichrome wires (No. 20 gauge U.S., 0.0100 inches in diameter) strung on a square mesh of 7.5 cm spacing on wood frames one meter square were supplied with 20 kVdc to produce air ions. The grids were hung one meter above the plant tops at the start of the experiments and remained there. The grids were

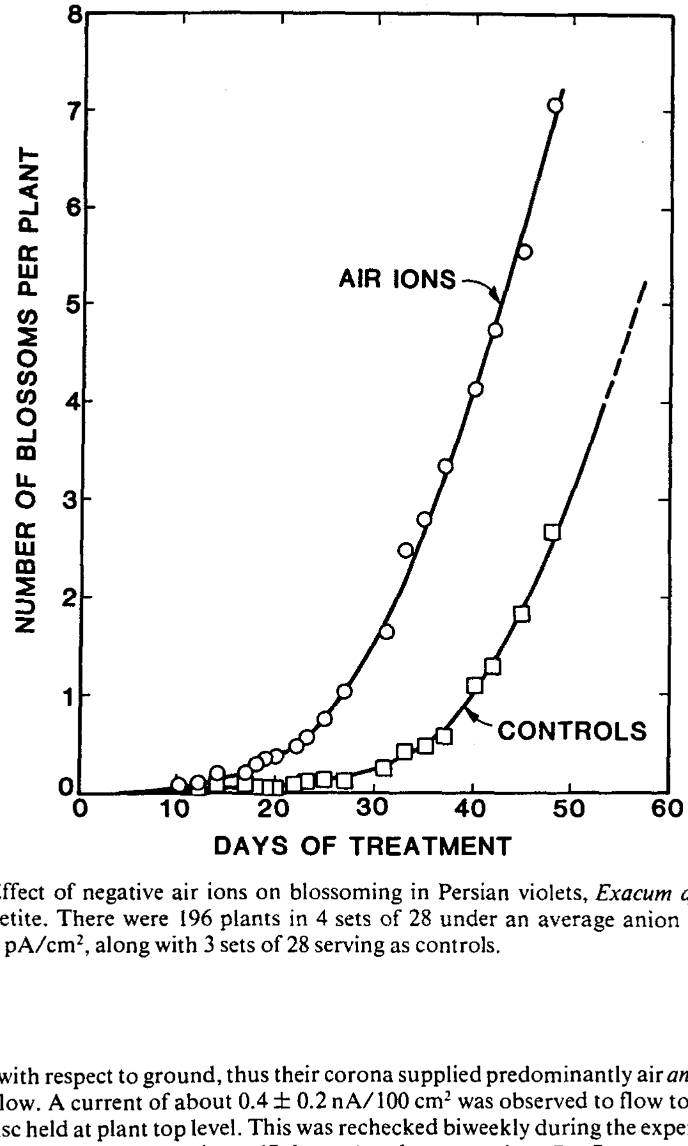

Fig. 3. Effect of negative air ions on blossoming in Persian violets, *Exacum affine*, var. petite. There were 196 plants in 4 sets of 28 under an average anion current of 4 pA/cm^2, along with 3 sets of 28 serving as controls.

negative with respect to ground, thus their corona supplied predominantly air *anions* to the plants below. A current of about 0.4 ± 0.2 $nA/100\ cm^2$ was observed to flow to a 100 cm^2 copper disc held at plant top level. This was rechecked biweekly during the experiment. At the outset, 49 seedling geraniums (*Pelargonium hortorum)* in a 7 x 7 array were set on grounded wire mesh beneath each of four grids constructed as above. Two grids were grounded, two were activated with the 20 kV negative supply, thus forming four test areas, with two serving as controls and two receiving air anions. Later the plants were set out on the 70th day under 6 grids in plots of 25, 25, 36, 36, 25, and 25 plants with 3 plots of controls (25, 25, 36) and 3 plots receiving ions. The seedlings were set out in 10 cm vented plastic pots in O.S.U. "mix" soil as 5.7 cm plants on 15 January 1979. On the 47th day they were watered with a "Peters" formula fertilizer to minimize a mild chlorosis which had become apparent. About 3 weeks subsequent to this the leaves of all plants appeared green and healthy. Blossom counts and plant heights were measured at suitable intervals. The plants were sacrificed on the 120th day to make biomass measurements. The outer row plants were discarded and not considered in the latter measurements.

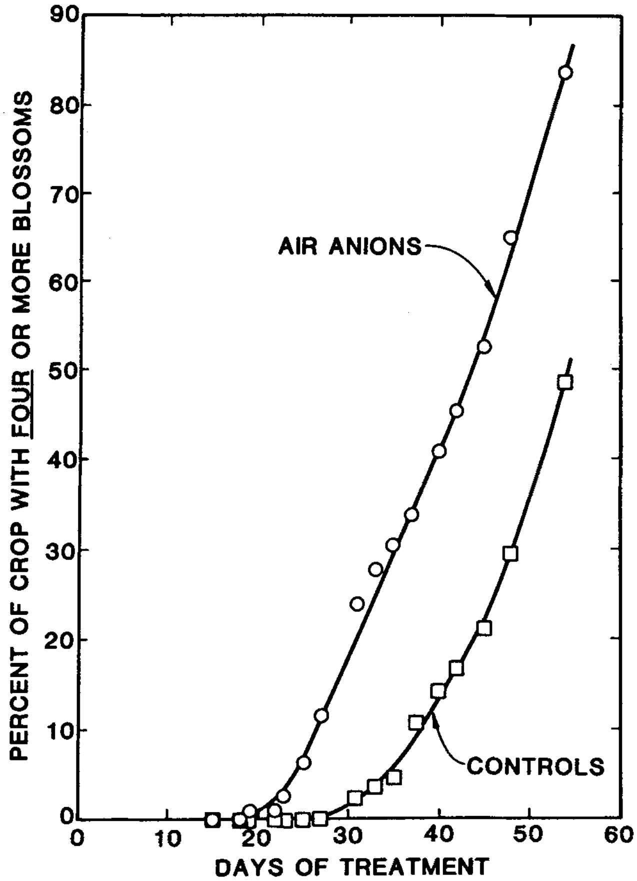

Fig. 4. Effect of air anions on blossoming rate in Persian violets, *Exacum affine*, var. petite. Note that the percentage of the crop which has four or more blossoms per plant (and is therefore judged by some horticulturists to be "salable") is attained by the anion-treated plants some two weeks ahead of the controls.

RESULTS AND CONCLUSIONS

A mild increase of the rate blossoming (inflorescences) was noted among the plants exposed to the air anions (Fig. 6). An increase in average plant height of about 15% among the ion cultured plants after 45 days was also evident, as can here confirm earlier observations of Murr (1965a, b) and of Bachman, Hademanos and Underwood (1971).

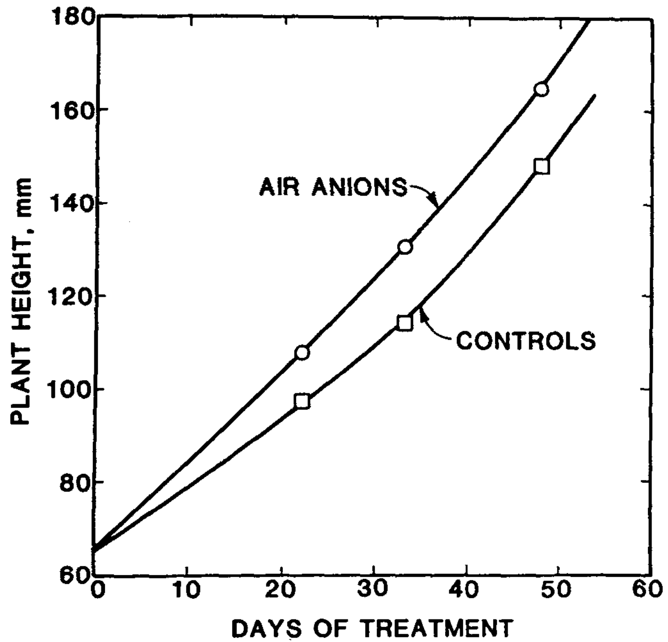

Fig. 5. Effects of air anions upon the plant height of Persian violets, *Exacum affine*.

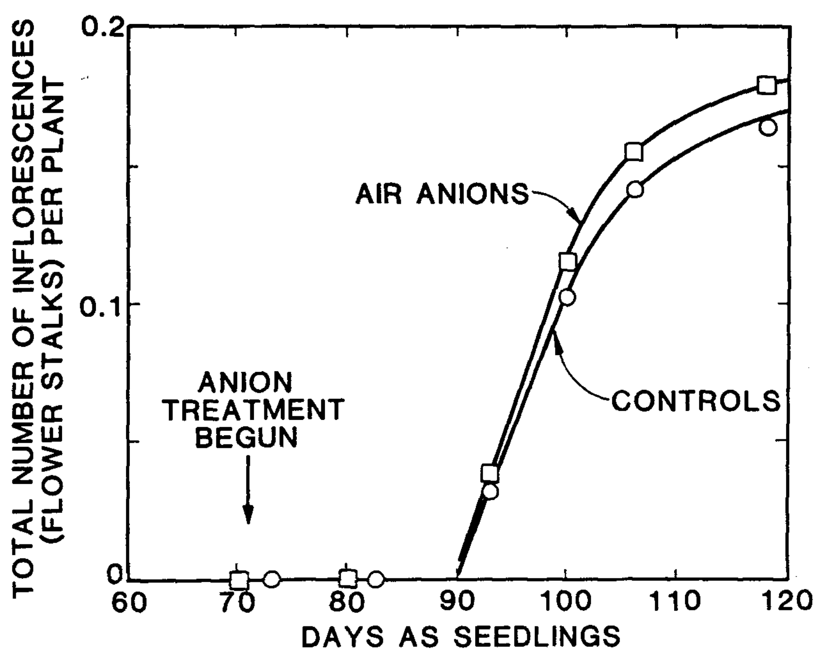

Fig. 6. Effects of air anions upon the blossoming rate in seedling geraniums (*Pelargonium hortorum*). The number of flower stalks (inflorescences) was determined as the treated plants were exposed to an average anion current of 4 pA/cm^2.

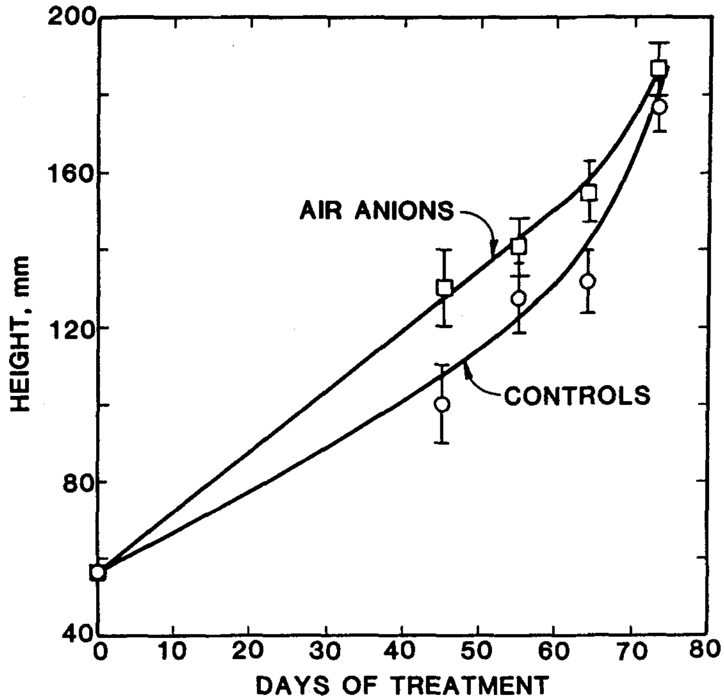

Fig. 7. Effects of air anions upon the growth rate of seedling geraniums (*Pelargonium hortorum*). The mean heights of 94 plants in each group are shown as a function of the duration of treatment. The error bars indicate the variance. Note that the differences between the treated and the control crop tend to disappear after a long time.

ACKNOWLEDGEMENT

The experiments described here were done in cooperation with William Hughes, W. Raymond Kays, Richard N. Payne, Garry K. Sites, Gregg Doolittle, Mike Staton and Karan Kaler. The project was supported by an O.S.U. Presidential Challenge Grant. Thanks are due John F. Thurlow for his stimulus and for his help with the literature search.

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