Foliar Uptake and Injury from Saline Aerosol[1]

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ABSTRACT

Pepper (*Capsicum annuum* L. cv. California Wonder), soybean (*Glycine max* L. Merrill cv. Prize), and tomato (*Lycopersicon lycopersicum* L. Karst. ex Farw. cv. Heinz 1350) plants were exposed to saline aerosols until incremental salt deposition levels of 0.2, 0.4, 0.6, and 0.8 mg Cl^- cm^{-2} of horizontal surface area were achieved. Foliar necrosis became evident on the 0.4 mg Cl^- cm^{-2} treatments after 3, 7, and 8 days on tomatoes, soybeans, and peppers, respectively, in an environmental chamber that simulated early morning dew between 0100 and 0700 PST. Severity of injury increased with increasing salt deposition and time. Foliar absorption of Na^+ and Cl^- was linearly related to the amount of salt deposition on leaves. No injury symptoms were apparent on any species at any salt deposition level when relative humidity (RH) was maintained at approximately 70% during the same period. Similar results were obtained in a second experiment where treated tomato, soybean, and pepper plants were compared at treatments of 70 and 100% RH during predawn hours but without dew formation. The injury at 100% RH, however, was not as pronounced as when plants were exposed to dew.

Additional Index Words: **pepper, soybean, tomato, sodium chloride, relative humidity, dew.**

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Airborne salts discharged into the atmosphere from salt water sources, e.g., cyclic salts, cooling towers, and sprinkler irrigation spray, drift downwind, and eventually some are deposited and accumulate on plants. Subsequent salt absorption through the leaves may injure the plant. Most observations of vegetation injured by airborne salts have been in close proximity to the seacoast (Edwards and Holmes, 1968; Karschon, 1958, 1964; Malloch, 1972; Moss, 1940; Natanson et al., 1978; Randall, 1974). Thus, injury has been observed primarily on native vegetation and ornamentals, but little knowledge exists about the tolerance of crop plants to airborne salts.

The increasing number of electrical power plants that use brackish-water evaporative cooling systems has intensified a need for information on the effects of saline aerosols on crops grown in the vicinity of these facilities. A number of greenhouse and field investigations have been conducted in recent years to determine the effects of airborne salts on various plant species (Armbruster et al., 1978; Curtis et al., 1979; Feder, 1978; Frances and Curtis, 1979; Hindawi et al., 1976; Lauver et al., 1978; McCune et al., 1977; Moser, 1975; Mulchi and Armbruster, 1975; Petolino and Leone, 1980; Silberman and McCune, 1978; Swain and Moser, 1972; Williams and Moser, 1975). However, few studies have examined these effects on crops under simulated field conditions where relative humidity (RH) and temperature fluctuate diurnally and dew forms in the predawn hours. As Talbot (1979) pointed out in his recent review, the validity of predicting adverse effects solely from total salt deposition is questionable without sufficient information on precipitation and dew formation. Moser (1975) found that high RH enhanced foliar uptake of Cl^- by bean leaves because of the hygroscopic properties of sea-salt particles. Chloride absorption continued throughout the experiment (24 hours) after salt spray application when RH was maintained continuously at 80%; however, at 60% RH, Cl^- uptake continued only for 4 hours immediately following misting. McCune et al. (1977) simulated cooling tower salt drift on 11 woody species and found that increasing the constant RH from 50 to 85% doubled the injurious effect of the treatment.

The present research was conducted to evaluate the effects of dew and high RH on foliar injury induced by salt deposition on pepper, soybeans, and tomatoes.

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MATERIALS AND METHODS

Plant Culture

Pepper (*Capsicum annuum* L. cv. California Wonder), soybean [*Glycine max* (L.) Merrill cv. Prize], and tomato [*Lycopersicon lycopersicum* (L.) Karst. ex Farw. cv. Heinz 1350] plants were grown under greenhouse conditions in 4-liter plastic containers filled with potting mix. All plants were irrigated daily with deionized water until seedling emergence, and then with 0.5 liter of complete nutrient solution. The nutrient solution consisted of 2.5 m*M* Ca $(NO_3)_2$, 3 m*M* KNO_3, 1.5 m*M* $MgSO_4$, 0.17 m*M* KH_2PO_4, 50 μM Fe (as sodium ferric diethylenetriamine pentaacetate), 23 μM H_3BO_3, 5 μM $MnSO_4$, 0.4 μM $ZnSO_4$, 0.2 μM $CuSO_4$, and 0.1 μM H_2MoO_4. After the plants developed 10 fully expanded leaves (tomatoes, 5–7 weeks; soybeans 4–5 weeks; and peppers, 8–10 weeks), they were moved to controlled-environment chambers for treatments.

Salt Deposition

The soil in all containers was covered with cellophane to prevent saline aerosols from entering the root media. Eight plants of one species were placed randomly in a plexiglass chamber 1.2 by 1.2 by 3 m high. A 4*N* saline solution, consisting of NaCl and $CaCl_2$ (9:1 chemical equivalent basis), was pumped through an ultrasonic spray nozzle (Sonimist model 700-1) at a rate of 25 ml min^{-1} and a pressure of 0.7 MPa to generate saline aerosols 2.0 m above the plant canopy. The nozzle rotated in a 4-cm diameter circle at 1 rpm to increase uniformity of the salt deposition. The aerosols were essentially dry when deposited on the aerial portion of the plants. Two plants were removed as each estimated salt deposition level of 0.2, 0.4, 0.6, and 0.8 mg Cl^- cm^{-2} was achieved. Actual deposition levels were determined as described below. One plant was placed into a controlled-environment chamber that produced dew between 0100 and 0700 PST, the other in a chamber that maintained RH at approximately 70% for the same period (see below). All treatments were replicated twice, and experiments were repeated three times.

Measuring Salt Deposition

Because the airborne salt concentration gradually increased with time, salt deposition (mg Cl^- cm^{-2} surface area) was not linearly related to exposure time. Hence, a method of monitoring continuous salt deposition levels was developed so that plants could be removed at desired treatment levels.

An open plexiglass dish (12 cm diameter) containing 300 ml of deionized water and a magnetic stirring bar was placed inside the exposure chamber. Water in the dish was continuously circulated through a digital electrical conductivity (EC) monitor. The EC readings were correlated to salt deposition levels determined with filter paper collectors. The EC of the solution in the dish was linearly related to amount of salt deposited. Circulation flow rates and positioning of the dish remained constant during the experiment.

Aerosol collectors (9-cm dry filter paper disks placed in petri dishes) were randomly distributed at foliage height to determine actual amounts of salt deposited on a horizontal plane. Aerosol collected on the filter paper disks was extracted with deionized water and Cl^- contents were determined by the Cotlove (1963) coulometric-amperometric titration procedure. Amounts of salt deposited for each treatment were obtained by averaging the amounts of Cl^- accumulated on two filter paper collectors that were removed with the plants at each treatment level. While these data provide a measure of salt deposition, they do not necessarily represent actual foliar deposition.

Sizes of the aerosol particles were determined by measuring the diameter of impaction craters on magnesium oxide-coated glass microscope slides (McCune et al., 1977; Stainer and Stow, 1976). More than 95% of the particles generated were between 5 and 20 μm in diameter.

Environmental Conditions

Lighting was natural sunlight through glass. Air pollutants were removed by passing incoming air through activated charcoal filters. Temperature and RH values fluctuated diurnally but out of phase with one another in both environmental chambers (Fig. 1). Temperature fluctuated between 25 and 13°C (average daytime highs and nighttime lows) in both chambers. After midnight, 100% RH was maintained in one chamber for approximately 6 hours. Enough moisture was introduced to produce dew. The other chamber was maintained at or below 70% RH during the same period. In a second experiment, treated plants were compared at approximately 70 and 100% RH during early morning hours, but without dew formation. Hereinafter, these three conditions will be referred to as the dew, 100% RH, and 70% RH treatments.

Plant Preparation and Analysis

Treated tomato, soybean, and pepper plants were removed from the controlled-environment chambers after 3, 7, and 8 days, respectively. All leaves >3 cm long, except those that were necrotic over >20% of the leaf surface, were detached from the plant. Leaves were then washed twice, 30 sec each, in separate 3-liter quantities of deionized water. The objective of the washing was to eliminate all surface salts without causing any efflux of Na^+ and Cl^- from within the tissue. The washing technique was tested by washing tomato, soybean, and pepper leaves, treated with 0.8 mg Cl^- cm^{-2}, in five consecutive 3-liter baths of deionized water for 30 sec in each. Analysis of the wash waters showed that essentially all of the Cl^- was removed in the first washing. Trace amounts of Cl^- found in subsequent washings indicated that the washing technique was effective without removing salt contained within the leaf tissue.

After leaves were washed, they were dried at 70°C and ground in a blender. Sodium, potassium, calcium, and magnesium were determined on nitric-perchloric acid digests of the leaf powder by atomic absorption spectrophotometry. Chloride was determined on dilute nitric-acetic acid extracts of the leaf material (Cotlove, 1963). Ion concentrations were reported in mol kg^{-1} of dried leaf material.

RESULTS

Foliar Injury

Within 24 hours after treatment with 0.8 mg Cl^- cm^{-2}, young pepper leaves (<3 cm in length) exhibited wilting in the chamber that simulated early morning dew. One day later, the margins and tips of previously wilted leaves developed chlorosis and necrosis. Many young leaves were epinastic. After 8 days, injury symptoms were evident at the 0.4 but not 0.2 mg Cl^- cm^{-2} level, and the severity of injury increased with increasing salt deposition. Chlorosis and necrosis spread unevenly over the entire leaf blade, and were not limited to margins and tips as in the case of saline sprinkling water injury (Ehlig and Bernstein, 1959). Crinkling of leaves became more pronounced with increasing leaf injury. This type of injury was observed by Hindawi et al. (1976) on bush beans during simulated salt-drift experiments. Some leaves abscised on the plants treated with 0.8 mg Cl^- cm^{-2}. Young leaves appeared to be more sensitive to saline aerosols than fully expanded leaves. In contrast to treated plants subjected to dew, treated plants held at 70% RH in the early morning hours showed no injury symptoms after 8 days.

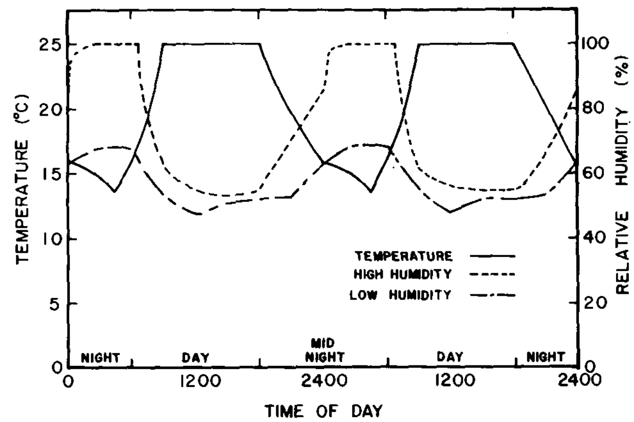

Fig. 1—Diurnal temperature and relative humidity fluctuations produced in the environmental chambers.

Soybeans developed slight chlorosis along the leaf margins within 48 hours after exposure to the 0.8 mg Cl^- cm^{-2} treatment when subjected to dew. After 7 days the lowest deposition level showing injury was 0.4 mg Cl^- cm^{-2}. Severity of injury increased with increasing salt level. Interveinal chlorosis developed evenly over the entire leaf surface in the 0.4 mg Cl^- cm^{-2} treatment, a symptom that was similar to that observed by others in salt deposition studies on soybean (Mulchi and Armbruster, 1975). Leaf margins were necrotic at the three highest treatment levels. Intercostal necrosis was frequent at the 0.6 mg Cl^- cm^{-2} level. Many of the leaves on the plants treated with 0.8 mg Cl^- cm^{-2} became completely necrotic and often abscissed. Sensitivity to saline aerosols was equal for leaves of all ages. No injury symptoms developed at any salt deposition level at 70% RH.

Young tomato leaves treated with 0.6 and 0.8 mg Cl^- cm^{-2} wilted after 24 hours and developed severe necrosis after 48 hours in the simulated-dew environment. Injury symptoms developed at the 0.4 mg Cl^- cm^{-2} level 72 hours after exposure almost exclusively on young leaves (<3 cm in length). Symptoms consisted of severe necrosis on younger tissue and slight chlorosis and necrosis on older tissue. Injury became more pronounced with increasing salt deposition. Most of the leaves on the top half of the shoot defoliated at the 0.8 mg Cl^- cm^{-2} treatment level. No injury symptoms were apparent at any salt deposition level where RH was maintained at 70%.

Injury symptoms were similar to those described above for all species in a second experiment where RH was maintained at 100% for 6 hours during the early morning hours, but without dew formation. The symp-

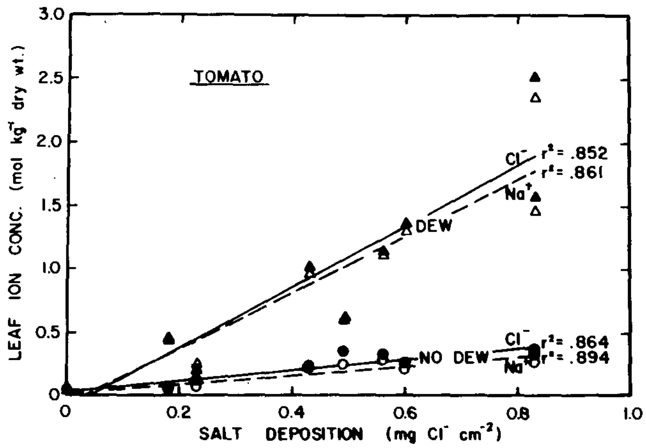

Fig. 2—Influence of dew on Na^+ and Cl^- absorption by tomato leaves during a 3-day period after deposition of various amounts of salt.

toms again developed on tomato, soybean, and pepper at the 0.4 mg Cl^- cm^{-2} level after 3, 7, and 8 days, respectively. Severity of injury increased with increasing salt deposition level. The injury, however, was not as pronounced as when plants were exposed to dew. Again no injury was observed on any species at any salt deposition level when RH was maintained at or below 70% at all times.

Foliar Absorption

Figures 2, 3, and 4 show the total accumulation of Na^+ and Cl^- in tomato, soybean, and pepper leaves 3, 7, and 8 days, respectively, after salt deposition. Dew markedly enhanced the rates of Na^+ and Cl^- uptake in all species. In the simulated-dew chamber, the leaf ion concentration for all species was a linear function of the salt deposition level. Slopes of this relationship varied among repeated experiments, but both linearity and the relative difference between the dew and 70%-RH treated plants were maintained. Slopes for Na^+ and Cl^- uptake by pepper in the 70% RH treatment were no more than 20 and 25%, respectively, of those in the dew treatment. Corresponding percentages were 8 and 28% for soybean, and 17 and 19% for tomato. Rate of Cl^- uptake was greater than that of Na^+ for all species in both environments, although the difference was small for tomato. Salt deposition on the leaves did not affect their Ca^{2+}, Mg^{2+}, or K^+ concentrations in any of the species.

When treated plants were subjected to 100% RH, soybeans and tomatoes were found to contain an average of 40 and 60%, respectively—as much Na^+ and Cl^- as plants exposed to dew. However, pepper leaves had the same Na^+ and Cl^- contents in both the dew and 100% RH treatments.

Leaf Na^+ concentrations at incipient injury ranged between 0.25–0.35, 0.40–0.50, and 0.45–0.80 mol kg^{-1} (dry weight) for pepper, soybean, and tomato leaves, respectively. The respective leaf Cl^- concentrations ranged between 0.30–0.60, 0.55–0.65, and 0.50–0.90 mol kg^{-1}.

DISCUSSION

Foliar absorption rates of Na^+ and Cl^- varied among species, as did tolerances of plants to airborne salts. Tomato leaves absorbed Cl^- readily and were the most severely injured. Soybean and pepper leaves, on the other hand, absorbed Cl^- more slowly and were slower to show injury. Our experiments, like those of others, showed that tolerance to salt spray does not necessarily parallel known plant tolerances to soil salinity (Maas and Hoffman, 1977) but was governed by the rate of foliar absorption. For example, peppers are more sensitive to soil salinity than tomatoes or soybeans, but our data showed that they were more tolerant than either species to saline aerosols. Similarily, corn, which is more sensitive to soil salinity than soybeans, was relatively more tolerant to cooling-tower spray (Mulchi and Armbruster, 1975). Because foliar absorption rates differ, susceptibility to foliar injury from saline aerosols should be determined for each species.

Foliar accumulations of Na^+ and Cl^- were linear functions of the salt deposition level for all crops exposed to dew or 100% RH conditions. Similar results were observed in a simulated salt deposition experiment with beans (Petolino and Leone, 1980). They found that Cl^- content in the leaf tissue increased linearly with increased exposure.

Susceptibility to foliar injury from saline aerosols also varied with the developmental stage of the leaf. Young tomato and pepper leaves (<3 cm in length) were more severely injured than older, fully developed leaves. McCune et al. (1977), found that younger leaves

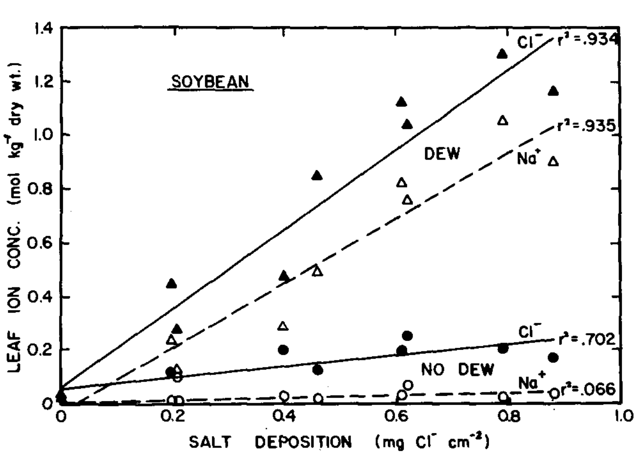

Fig. 3—Influence of dew on Na^+ and Cl^- absorption by soybean leaves during a 7-day period after deposition of various amounts of salt.

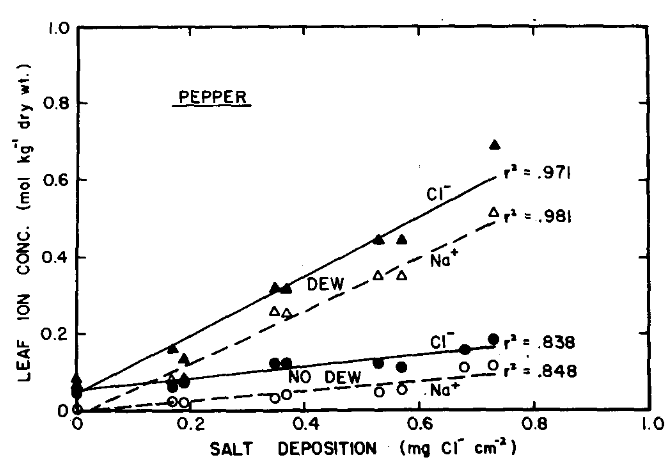

Fig. 4—Influence of dew on Na^+ and Cl^- absorption by pepper leaves during a 8-day period after deposition of various amounts of salt.

of deciduous woody species were more sensitive to saline aerosols than older leaves, whereas the converse was true in conifers.

Salt deposited on the leaf surface must dissolve to be absorbed into the leaf tissue and cause injury. Previous studies (McCune et al., 1977; Moser, 1975) showed that high RH (80–85%) enhanced foliar absorption rates because of the hygroscopic nature of the salts. However, these studies were conducted at constant RH. Under field conditions, temperature and RH fluctuate diurnally with maximum RH or dew formation occurring in the predawn hours when temperatures are generally lowest. Moser (1975) found that after salts dried on bean leaf surfaces at 60% RH, Cl^- uptake ceased. However, at 80% RH, Cl^- uptake continued. We found that when ambient RH remained below 70%, even heavy levels of deposited salt (0.6–0.8 mg Cl^- cm^{-2}) did not induce injury in peppers, soybeans, and tomatoes. Although ion absorption rates decrease with decreasing temperature (Smith and Robinson, 1971), sufficient Na^+ and Cl^- accumulated during the humid predawn hours, when temperature ranged from 12 to 18°C, to cause injury in all three species. Thus, early morning dew or even high RH without dew formation may pose a serious threat to crops growing in close proximity to evaporative cooling towers using saline water.

Using available salt deposition models, Roffman and Roffman (1973) calculated that a 1000-MW natural and mechanical draft cooling tower utilizing 35,000 ppm seawater and having a drift rate of 0.063 m^3 sec^{-1} could deposit up to 0.34 mg Cl^- cm^{-2} within a few kilometers of the tower, over a 2-month period. Although one cannot accurately predict the long-term effects these levels will have on susceptible crops in the field, it is clear that some crops could be adversely affected. Studies of incremental deposition on susceptible species (e.g., tomato) over longer durations (e.g., 2–4 months) with low deposition rates need to be conducted under fluctuating environmental conditions typical of field conditions.

ADDENDUM

Foster and Maun recently noted that the foliage of white cedar (*Thuja occidentalis* L.) developed necrosis within 1 week after salt deposition when plants were held in an environmental chamber at 91–100% RH. However, the only injury observed when the RH was maintained between 50 and 70% after salt deposition was a slight leaf-tip chlorosis 20 days later.

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