Suppression of Fusarium Crown and Root Rot of Asparagus with Sodium Chloride

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ABSTRACT

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The application of sodium chloride on asparagus beds, an old practice that has been abandoned, suppressed Fusarium crown and root rot caused by *Fusarium oxysporum* and *F. proliferatum*. Spring applications of NaCl (560–1,120 kg/ha) suppressed the disease under various field conditions and were superior to KCl, KNO_3, NH_4NO_3, or $Ca(NO_3)_2$ in retarding asparagus decline and increasing marketable yields. In the greenhouse, applications of NaCl solutions to asparagus resulted in significant increases in fresh weight and suppressed the fraction of diseased roots as well as the number of colony-forming units of *F. oxysporum* and *F. proliferatum* recovered per centimeter of root (cfu/cm). There were positive correlations between the fraction of diseased roots, cfu/cm, and the ratio of K^+ to Cl^- concentrations in plants that were grown in noninfested soils. Chloride uptake was negatively correlated with the fraction of diseased roots. Uptake of Na^+ was restricted and not as correlated with disease suppression as was Cl^- uptake. Fern analyses of field grown plants treated with NaCl confirmed the strong association between yield increases, suppression of Fusarium crown and root rot, Cl^- uptake, and a K:Cl ratio in the tissue of less than 3. These applications of NaCl were not herbicidal to weed species or fungicidal to soil populations of *Fusarium* spp., but they did result in significant reductions of rhizosphere populations in treated plants when compared with untreated plants. Sodium chloride may suppress Fusarium crown and root rot through a fungistatic effect and/or through manipulation of host resistance.

Additional keywords: Asparagus officinalis disease management.

Fusarium crown and root rot of asparagus (*Asparagus officinalis* L.), caused by *Fusarium oxysporum* (Schlechtend.:Fr.) and by *F. proliferatum* (T. Matsushima) Nirenberg (syn. *F. moniliforme* J. Sheld.), has limited production in the northeastern United States (12,24,33,35) and elsewhere (8,26). Yield loss results from smaller and fewer spears and from crown death. The fungi cause extensive rotting of feeder and storage roots, vascular discoloration of the crown and stems, fern chlorosis, wilt, and death. The pathogens are common in most soils (12,24), and effective chemical controls are lacking (35).

This disease was the primary cause for the yield decline during the 1950s to 1960s in production areas in the Connecticut River Valley, New Jersey, Michigan, and California. Coincident with this decline in asparagus yield was a gradual discontinuation of the practice of dressing asparagus fields with rock salt (NaCl). Although NaCl is toxic to most plants, asparagus is among the most saline-tolerant plants grown commercially (22). Salting to improve asparagus yields and to suppress weeds was once common in asparagus culture, and early gardening books (3,5,36,58) and scientific publications (45–47,57) recommended liberal applications of rock salt. The practice was gradually abandoned in most commercial operations in the 1940s for reasons that are unclear, but possibly because of the advent of synthetic herbicides.

Past work demonstrated that artificially inoculated asparagus plants treated with NaCl had less disease, less fungal colonization of roots, and greater size than untreated plants or plants treated with KCl (16). These observations and the past association between rock salt and asparagus indicated that NaCl applications should be reevaluated for suppressing Fusarium crown and root rot in the field. Many reports have demonstrated disease control in the field with chloride salts (7,23,49,51,54,60). The objectives of this study were to determine the effect of NaCl applications on Fusarium crown and root rot of asparagus and on inoculum densities of *F. oxysporum* and *F. proliferatum,* and to determine the relationships between plant tissue nutrient concentrations and disease suppression.

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MATERIALS AND METHODS

Production of greenhouse plants, inoculum, and soil medium. Asparagus cultivar Mary Washington (Comstock Ferre Seed Co., Wethersfield, CT) was used in all greenhouse experiments. Seeds were surface-disinfested in 0.5% NaOCl (10% household bleach) for 30 min followed by an acetone/benomyl infusion (11), then dried and germinated on 0.6% water agar (18). Seedlings were placed in 36-cell plastic trays containing commercial potting mix (ProMix BX, Premier Brand, Inc., New Rochelle, NY) for 12 wk. Each cell received 50 ml of Hoagland's solution (29) every week beginning 7 wk after germinated seeds were placed in soil. Transplants then were washed to remove the soil from the roots, inspected to make certain that roots were white and healthy, and weighed to choose uniform transplants between 5 and 7 g in fresh weight.

Single-spore cultures of *F. oxysporum* and *F. proliferatum* were obtained from colonies growing from infected asparagus crowns and stored on silica gel (59). Inocula of *F. oxysporum* (isolate CT661) and *F. proliferatum* (isolate P214) were prepared from colonized asparagus residues. Fifty grams of dried, ground (1.41-mm mesh size) stalks and crowns were combined with 25 ml of distilled water in 500-ml flasks and autoclaved for 1 h on two consecutive days. The residues were seeded with colonized or sterile potato-carrot agar (13) plugs (6 mm diameter), incubated at 25 C for 4 wk, and then air-dried. Residues were mixed with separate lots of soil at 1.0 g of residue per liter of soil. Because asparagus residues were not available in later studies, inoculum was grown similarly on tall fescue (*Festuca arundinacea* Schreb. 'Creeping Red Fescue') seeds. There was no apparent difference between the inoculum preparations and the disease severity (W. H. Elmer, *unpublished data*).

Soil consisted of 1 part sand to 2 parts (v/v) commercial potting mix (ProMix C, Premier Brand, Inc.). The soil characteristics were as follows: bulk density, 0.7 g/cm^3; NO_3-N, 0.0 μg/g; NH_4-N, 0.0 μg/g; PO_4-P, 100.0 μg/g; exchangeable K^+, 6.0 meq/100 g; exchangeable Ca^{2+}, 8.0 meq/100 g; exchangeable Mg^{2+}, 2.5 meq/100 g; and exchangeable Cl, 1.7 meq/100 g using the procedures of Lunt et al (38).

Influence of Ca, K, and NaCl rate on disease of asparagus. To assess the relationship between NaCl, Ca, and K nutrition with disease, asparagus transplants were individually transplanted into plastic 1-L pots filled with 0.7 kg of noninfested soils or soil infested with either *F. oxysporum* or *F. proliferatum*. Three nutrient solutions were prepared from $Ca(NO_3)_2$ and/or KNO_3 to yield concentrations of 15 μmol/L of NO_3^-, but they differed in Ca^{2+} and K^+ concentrations. Solutions contained 7.5 μmol/L of Ca^{2+}, 5.0 μmol/L of Ca^{2+} + 5.0 μmol/L of K^+, or 15.0 μmol/L of K^+. NaCl was added to each solution at 0, 1, 2, or 4 g/L (equal to 0, 17.1, 34.2, or 68.4 μmol/L of Cl^-, respectively). Thus, 12 different fertilizer treatments were each applied in 100-ml portions to five replicate pots weekly for 10 wk. The pots were arranged on greenhouse benches in a complete randomized block design with five blocks (one replicate pot per block). Two to 3 days after each application, pots were flushed with 200–300 ml of deionized water to discourage saline conditions, and soil was kept moist until the next application. After 10 wk, soil was washed from the plant, and roots and ferns were weighed separately. Disease was assessed as described below. Ferns were air-dried to constant weights, reweighed, and analyzed for K^+, Na^+, Ca^{2+}, Mg^{2+}, PO_4^{3-}, and Cl^- as described below. The experiment was repeated once.

Soil, root, and disease assays. Rhizosphere soil was sampled from each plant by gently dislodging the soil from the root ball. Soil that tightly adhered to roots was removed by vigorously shaking the root systems until 5–10 g of soil was collected (52). Soil was air-dried, passed through a 2-mm sieve, and stored in plastic bags at 4 C until assayed 1–4 wk later.

A study with the same fertilizer treatments as above was run concurrently in 1-L plastic pots filled with soil infested with *F. oxysporum* or *F. proliferatum* and left fallow. Pots were treated as described above. The experimental design was a complete randomized block with three blocks (one replicate pot per block). This soil was sampled after 10 wk by removing three soil cores from each pot with a cork borer (1.7 cm diameter). The three soil cores were bulked and processed like the rhizosphere soils.

Two 2-g subsamples from each soil sample were separately suspended in 200 ml of distilled water and agitated on a magnetic stir plate for 10–15 min. Soil suspensions (0.1 ml) were spread on each of 3–5 petri plates filled with selective medium (34), and plates were incubated for 5–8 days on laboratory benches at ambient temperatures. Colonies of *F. oxysporum* or *F. proliferatum* in each subsample were identified by colony characteristics and conidiophore morphology (42). Numbers from subsamples were expressed as the number of colony-forming units per gram of soil, averaged, and analyzed for treatment effects.

The fraction of diseased roots and the extent of root infection by the *Fusarium* spp. were determined on each plant. Root systems were washed for 3–5 min in tap water, placed into 0.02% NaOCl (4% household bleach) for 4 min, and rinsed with tap water. Excess water was removed by pressing roots between absorbent paper towels. Young feeder roots (1–3 cm in length), which are the most commonly infected by these fungi (53), were removed and placed onto three Falcon (10 × 10 cm) Integrid petri dishes (Becton Dickinson Co., Lincoln Park, NJ) that contained 15 ml of medium selective for *Fusarium* spp. (34). The total length of these roots and the fraction of root length with lesions were estimated by the modified line-intersect method (55). After petri dishes were incubated at 20–25 C for 5–7 days, colonies of *F. oxysporum* or *F. proliferatum* growing from the roots were counted and expressed as colony-forming units per centimeter (cfu/cm) of root.

Field studies. Unless noted otherwise, crowns or transplants of asparagus cultivar Mary Washington were used in all field plots. Conventional insect management was practiced, and weeds were removed by hand so any herbicidal effect of the NaCl could be detected. Soils were limed in the fall as required to maintain soil neutrality (pH 6.5–7.0).

Field 1 was planted in 1984 in Windsor, CT, on a Wethersfield fine loamy sand. Plots were prepared by placing 20 12-wk-old transplants 30 cm apart in rows that were 6 m long and spaced 1.5 m apart. In the spring of 1985 and 1986, an application (112 kg/ha) of 10-10-10 (N-P-K) fertilizer was broadcast over the top of the crowns. In late April 1987 spears that were longer than 22.5 cm were cut every 2–3 days six times, trimmed to 22.5 cm, counted, and weighed. After harvest (late May), granular applications (112 kg/ha of N) of $Ca(NO_3)_2$ or KNO_3, or no N, were combined with NaCl or KCl (1,120 kg/ha), or no Cl, and broadcast over the top of the crowns. Therefore, nine treatments were applied to 36 plots (four plots per treatment) in a complete randomized block design. In spring 1988, the spears were harvested for the same duration as in 1987.

Field 2 was planted in 1986 on a Cheshire fine sandy loam in Hamden, CT. Plots were prepared by planting five 1-yr-old crowns 30 cm apart in trenches approximately 25 cm deep. Trenches were half filled with soil and gradually filled up over the next 2 yr according to conventional recommendations. Plots were 1.8 m long and spaced 1.5 m apart. After planting, applications (112 kg/ha) of 10-10-10 (N-P-K) fertilizer were broadcast over the top of the crowns. In April of 1987–1991, granular applications (56 kg/ha of N) of NH_4NO_3 or $Ca(NO_3)_2$, combined with NaCl or KCl (560 kg/ha), or no Cl, were broadcast over the top of the crowns. Thus, six treatments were applied to 24 plots (four plots per treatment) in a complete randomized block design. The treatments were applied again in June of each year. Spears that were longer than 22.5 cm were cut every 2–3 days, trimmed to 22.5 cm, counted, and weighed—five times in 1988, nine times in 1989, 12 times in 1990, and 12 times in 1991. Plot vigor was rated in July 1990 on a scale of 1–3, where 1 = vigorous green foliage with a dense canopy, 2 = sparse foliage, but no or slight chlorosis and no fern death, and 3 = chlorotic or light green ferns accompanied with sparse, dying, or dead foliage.

Field 3 was established in Hamden, CT, on a Cheshire fine sandy loam in 1989. Twelve plots, 1.2 m long and spaced 3 m apart, were dug as described for field 2. Three 1-yr-old Mary Washington crowns were planted in each of six plots, and the other six plots each were planted with three crowns of Syn 4-56 (Nourse Farms, South Deerfield, MA). To accelerate disease development, plots were artificially infested by spreading 10 g of colonized asparagus residues in each plot before the trenches were filled. In July 1989 three plots of each cultivar received granular applications of NaCl (560 kg/ha) and NH_4NO_3 (56 kg/ha of N); the other three plots of each cultivar received only NH_4NO_4 (56 kg/ha of N). The experimental design was a complete factorial (two cultivars × two NaCl treatments) randomized block (three plots per treatment). Treatments were applied again in July 1990. In 1990 stand counts, expressed as the number of stems per crown, and plot vigor ratings were recorded. Because asparagus plantings are not conventionally harvested until the third year, yield was not taken from field 3.

Soils in fields 2 and 3 were sampled in August or September with a soil auger (2 cm diameter) approximately 15 cm from the crowns to a depth of 22 cm. Four soil cores were removed from each plot, bulked, and assayed for population densities of *Fusarium* spp. as described above. Root colonization also was evaluated at these times by removing the asparagus roots from the soil samples and assaying them as described above.

Tissue sampling and elemental analyses. In September 1990 one stalk was cut at ground level from each of three to five plants per plot in field 2 and from two plants per plot in field 3. Stalks in each plot were bulked, air-dried in the greenhouse, and removed of berries. Aboveground portions of plants in pots from greenhouse experiments were similarly air-dried. Each tissue sample was ground in a Wiley mill and passed through a 1-mm sieve. Free chlorides (Cl^-) and phosphates (PO_4^{3-}) were extracted by agitating two 0.5-g portions of material in 100 ml of deionized water on a wrist-action shaker (Burrell Co., Pittsburgh, PA) for 15–30 min. Aqueous extracts were passed through Whatman No. 2 filter paper, and the filtrate was analyzed for Cl^- and PO_4^{-3} using an ion chromatograph (Dionex 2010i, Dionex Corp., Sunnyvale, CA). Tissue samples were prepared for analysis of K, Ca, Mg, and Na by heating 0.25-g tissue samples in 4 ml of sulfuric acid and slowly oxidizing with 10 ml of 50% hydrogen

peroxide. Samples were brought up to 100 ml with distilled water and analyzed by inductively coupled plasma emission spectroscopy on an ARL 3520 ICP-OES spectrophotometer (Fison Instruments, Deerborn, MI). Blanks always were included to adjust sample measurements. Ion concentrations were expressed as micromoles per gram of plant tissue.

Statistical procedures. Greenhouse experiments were analyzed by analysis of variance (ANOVA), and linear and quadratic contrasts were computed to show treatment effects. Relationships among ion concentrations and disease evaluations were examined by linear correlations generated by Pearson's correlation matrix and include data from both repetitions. Coefficients were tested for significance by linear regression. The effects of the different salt treatments on yield in field 1 were analyzed using the yield data from the previous year in a covariate analysis to account for the initial plot-to-plot variability. A repeated measures univariate ANOVA was used to analyze the 1988–1991 yield data from field 2. Because all plot vigor ratings and the K:Cl ratios in the fern tissue were not normally distributed, the nonparametric Kruskal-Wallis test and the modified Friedman test (9) were used. All analyses were computed using Systat Statistical Systems software (Systat, Inc., Evanston, IL).

TABLE 1. Effect of calcium and/or potassium combined with increasing rates of NaCl on fresh weight of asparagus grown in noninfested soils or soils infested with *Fusarium oxysporum* or *F. proliferatum*

Treatment[y]	Fresh plant weights (g)		
	Control	*F. oxysporum*	*F. proliferatum*
Averaging over all Ca/K treatments			
NaCl, 0 g/L	31.3[z]	20.2	13.9
NaCl, 1.0 g/L	34.4	18.5	14.2
NaCl, 2.0 g/L	40.0	21.5	18.0
NaCl, 4.0 g/L	37.5	27.6	28.9
Contrast (*P*)			
Linear	NS	0.046	< 0.001
Quadratic	NS	0.038	< 0.000
Averaging over all NaCl treatments			
Ca	35.5	19.9	21.7
Ca/K	36.3	21.1	15.1
K	35.7	24.9	19.4
Contrast (*P*)			
Ca^{2+} vs. no Ca^{2+}	NS	NS	NS
K^+ vs. no K^+	NS	NS	NS

[y] Cations applied as NO_3^- salts; Ca = 7.5 μmol Ca^{2+}, Ca/K = 5.0 μmol Ca^{2+} + 5.0 μmol K^+, and K = 15 μmol/ml K^+.

[z] Values represent the mean of five replicates averaged over the respective treatment.

RESULTS

Greenhouse nutritional studies. Treatment effects were similar in both repetitions of the study based on a nonsignificant *F* test at $P = 0.05$; the results from the second repetition are presented (Table 1). No significant interaction was detected between the NaCl rates and Ca/K treatments on asparagus growth, so only main effects are discussed. The rate of NaCl had a significant linear and quadratic effect on fresh weights of plants grown in soil infested with *F. oxysporum* or *F. proliferatum,* but it did not affect fresh weights of plants growing in noninfested soil. *F. proliferatum* was more virulent than *F. oxysporum,* and plants treated with the high rate of NaCl more than doubled in size when compared with untreated infected plants. The Ca/K regimes did not affect growth of plants grown in infested or noninfested soils.

No treatment interaction was detected on the fraction of diseased roots or the cfu/cm. The fraction of diseased roots decreased with increasing rates of NaCl (Table 2). The highest NaCl rate suppressed the fraction of diseased roots approximately 20% for both *Fusarium* spp. Root colonization was not significantly affected by NaCl, but trends were consistent with the effect of NaCl on the fraction of diseased roots. Concentrations of Na^+ and Cl^- increased in the tissue as NaCl rates increased, whereas K^+ concentrations decreased as NaCl rates increased. Treatments had no significant effect on concentrations of Ca^{2+}, PO_4^{3-}, or Mg^{2+}, and the data are not presented. No significant effects were detected in response to the different Ca/K treatments.

The correlation coefficient between the fraction of diseased roots and cfu/cm in plants grown in soils infested with *F. oxysporum* was similar to those plants grown in soil infested with *F. proliferatum* (data not shown). Combining both data sets revealed a linear relationship between the fraction of diseased roots (FDR) and the cfu/cm of root (CFU): $FDR = -0.11 + 0.29 \times CFU$ (df = 46, $P < 0.001$) (Table 3). This equation predicted that asymptomatic roots contained on the average 1.0 cfu/2.9 cm of asparagus root and that an average 0.35 cfu/cm increase was associated with every 0.1 unit increase in the fraction of roots with lesions. The fraction of diseased roots and the cfu/

TABLE 2. Effect of calcium and/or potassium combined with increasing rates of NaCl on the fraction of diseased roots and root colonization by *Fusarium oxysporum* or *F. proliferatum*, and analysis of fern tissue

Treatment[v]	*F. oxysporum* cfu/cm[w]	*F. oxysporum* FDR[w]	*F. proliferatum* cfu/cm[w]	*F. proliferatum* FDR[w]	K^+ (μmol/g of tissue[x])	Na^+ (μmol/g of tissue[x])	Cl^- (μmol/g of tissue[x])	K:Cl	Na:Cl
Averaging over all Ca/K treatments									
NaCl, 0 g/L	0.96[y]	0.11	0.83	0.14	1.04	0.04	0.17	5.1	0.02
NaCl, 1.0 g/L	0.80	0.09	0.83	0.14	1.02	0.05	0.36	2.9	0.13
NaCl, 2.0 g/L	0.77	0.08	0.77	0.09	0.93	0.12	0.39	2.4	0.30
NaCl, 4.0 g/L	0.80	0.07	0.69	0.06	0.85	0.26	0.43	2.1	0.43
Contrast (*P*)									
Linear	NS	0.05	NS	0.04	0.04	0.007	<0.001	0.001[z]	0.043[z]
Quadratic	NS	NS	NS	NS	NS	0.021	<0.001	0.001	0.013
Averaging over all NaCl treatments									
Ca	0.80	0.09	0.73	0.09	0.88	0.12	0.37	2.7	0.30
Ca/K	0.76	0.07	0.84	0.12	0.97	0.14	0.35	2.9	0.30
K	0.94	0.10	0.78	0.12	1.04	0.11	0.37	3.0	0.30
Contrast (*P*)									
Ca^{2+} vs. no Ca^{2+}	NS	NS	NS	NS	NS	NS	NS	NS	NS
K^+ vs. no K^+	NS	NS	NS	NS	NS	NS	NS	NS	NS

[v] Cations applied as NO_3^- salts; Ca = 7.5 μmol Ca^{2+}, Ca/K = 5.0 μmol Ca^{2+} + 5.0 μmol K^+, and K = 15 μmol/ml K^+.

[w] cfu/cm = Colony-forming units of *F. oxysporum* or *F. proliferatum* per centimeter of root length; FDR = fraction of diseased root/centimer of root (discolored roots/total root length). Root lengths were estimated by the modified line-intersect method (55).

[x] Fern analyses were done on plants grown in noninfested soils.

[y] Values represent the mean of five replicates averaged over each treatment.

[z] Contrast computed using rank transformation (9) with Kruskal-Wallis test.

cm were both linearly correlated with the K^+ to Cl^- (K:Cl) ratio in the fern tissue. The equation that best fitted this relation was FDR = 0.3 + 0.03 K:Cl (df = 46, $P < 0.001$), which implied that for every 1.0 unit reduction of the K:Cl ratio in the fern tissue, the fraction of diseased roots was suppressed 0.03.

Treatment effects on the soil densities of either fungus did not vary between the two repetitions based on an F test at $P = 0.05$, and the combined results of both experiments are presented. An interaction between Ca/K treatments and the NaCl rate affected the number of colonies of *F. oxysporum* or *F. proliferatum* detected in rhizosphere soils (Table 4). In general, the populations of both fungi were greater in soils treated with K and decreased in all Ca/K treatments as the rate of NaCl increased. Populations of either fungus were not affected by this interaction in fallow soils.

Field studies. The initial plot-to-plot variability in field 1 was compensated by using the plot yield taken before the application of the fertilizer treatments as a covariate in an analysis of covariance. No interaction occurred between the nitrogen fertilizers and chloride salts, so only the main effects are presented (Table 5). Marketable spear weights and spear numbers in untreated plots declined in 1988. However, the amount of yield loss was significantly lower when NaCl was applied individually or combined with an N fertilizer; KCl was significantly less effective than NaCl. Of the N treatments, only KNO_3 caused a marginal increase in yield.

A repeated measures univariate analysis of variance showed the 1988–1991 marketable yields from plots in field 2 were most affected by the year of harvest, which was obviously due to the extension of the harvest period each year (Table 6). A significant interaction, however, occurred between the N form and the Cl form and between N form × Cl form × year. Combinations of NH_4NO_3 + NaCl produced the greatest yields, and $Ca(NO_3)_2$ + KCl produced the next largest yields. Analysis of the fern tissue in 1990 showed K:Cl ratios outside the range of 2.6–3.0 were generally associated with lower-yielding symptomatic plots. Soil densities of *Fusarium* spp. did not significantly differ among treatments, and weed growth was not affected by the salt treatments (data not shown).

No significant interaction occurred between the cultivars and the NaCl treatments in field 3, but both cultivars developed larger and more vigorous ferns when treated with NaCl compared with untreated plants (Table 7). Applying NaCl had no effect on the fraction of diseased roots that were recovered from the soil cores; however, these NaCl applications did result in significant reductions in cfu/cm of root when compared with untreated plants. Roots from Syn 4-56 had significantly less colonization than roots from Mary Washington. Asparagus plots that contained high fern concentrations of Cl^- and low K:Cl ratios were usually rated as being more vigorous and healthy than plots with lower Cl^- concentrations and higher K:Cl ratios. No significant difference in soil densities of *Fusarium* spp. were found between salt-treated and untreated plots (data not shown), and there was no indication that NaCl suppressed weed growth in these plots (data not shown).

TABLE 3. Correlation coefficients between the fraction of diseased roots (FDR), root colonization by *Fusarium oxysporum* and *F. proliferatum* (cfu/cm), and nutrient concentrations in asparagus treated with calcium and/or potassium combined with increasing rates of NaCl

		Elemental nutrients[x]				Elemental ratios		
Variables[y]	cfu/cm	Mg^{+2}	K^+	Na^+	Cl^-	K:Na	K:Cl	Na:Cl
cfu/cm	...	0.27	−0.10	−0.26	−0.39**[z]	0.04	0.61***	0.15
FDR	0.67***	0.34*	0.42**	−0.46**	−0.68***	0.21	0.74***	−0.35*

[x] Tissue analyses conducted on plants grown in noninfested soils and include data from two experimental repetitions.
[y] cfu/cm = Colony-forming units of *F. oxysporum* or *F. proliferatum* per centimer of root length; FDR = fraction of diseased root determined on the length (cm) of discolored roots/total root length. Root lengths were estimated by the modified line-intersect method (55).
[z] *, **, or *** = Significant at $P = 0.05$, 0.01, or 0.001, respectively.

TABLE 4. Effect of calcium and/or potassium combined with increasing rates of NaCl on soil densities of *Fusarium oxysporum* and *F. proliferatum* in asparagus rhizosphere soil and in fallow soil

	Rhizosphere soil (cfu × 1,000/g)[x]		Fallow soil (cfu × 1,000/g)[x]	
Treatment[y]	*F. oxysporum*	*F. proliferatum*	*F. oxysporum*	*F. proliferatum*
Ca	14.4[z]	3.4	35.4	6.1
Ca + NaCl, 1.0 g/L	4.4	2.4	25.0	2.2
Ca + NaCl, 2.0 g/L	8.4	1.4	42.5	4.9
Ca + NaCl, 4.0 g/L	2.2	1.5	32.3	5.0
Ca/K	30.0	2.8	23.0	17.3
Ca/K + NaCl, 1.0 g/L	11.2	1.2	33.0	11.6
Ca/K + NaCl, 2.0 g/L	7.0	0.8	29.1	2.0
Ca/K + NaCl, 4.0 g/L	1.4	1.0	28.7	3.8
K	24.8	4.2	24.1	8.1
K + NaCl, 1.0 g/L	23.2	4.6	42.4	8.4
K + NaCl, 2.0 g/L	5.4	2.6	40.6	11.7
K + NaCl, 4.0 g/L	12.4	1.2	26.4	7.3

Analysis of variance

Source	df	P	P	df	P	P
Ca/K	2	0.02	0.02	2	NS	0.025
NaCl rate	3	<0.001	NS	3	NS	0.001
Ca/K × NaCl rate	6	<0.001	0.001	6	NS	NS
Error	48			24		

[x] Rhizosphere soil was sampled from asparagus roots; fallow soil was sampled from pots not planted with asparagus transplants.
[y] Cations applied as NO_3^- salts; Ca = 7.5 μmol Ca^{2+}, Ca/K = 5.0 μmol Ca^{2+} + 5.0 μmol K^+, and K = 15 μmol/ml K^+.
[z] Values show means of five replicates from two repetitions averaged over treatment.

DISCUSSION

Sodium chloride applied to asparagus suppressed Fusarium crown and root rot in the greenhouse and in naturally infested field plots. More importantly, marketable spear weights from asparagus plants affected by Fusarium crown and root rot were increased when NaCl was applied. These experiments are the first in which NaCl was superior to KCl in ameliorating plant disease under field conditions. Sodium chloride amendments may have wide applicability in asparagus disease management by restoring productivity to old asparagus fields and promoting vigor in young ones.

TABLE 5. Effect of chloride salts and calcium and potassium nitrate on asparagus yield decline (field 1)

	Marketable spear yield[w]			
	Before treatment (1978)		After treatment (1988)	
Treatment[x]	Number	Weight (kg)	Number	Weight (kg)
Averaging over N treatments				
No Cl	37.5[y]	0.59	14.6	0.18
KCl	39.2	0.59	19.6	0.29
NaCl	41.7	0.66	30.1	0.49
Contrasts (P)[z]				
Cl^- vs. no Cl^-	NS	NS	<0.001	0.002
KCl vs. NaCl	NS	NS	0.030	<0.001
Averaging over CL^- treatments				
No NO_3	44.8	0.70	22.8	0.29
$Ca(NO_3)$	36.7	0.53	18.6	0.26
KNO_3	40.0	0.61	29.0	0.40
Contrasts (P)[z]				
No NO_3^- vs. NO_3^-	NS	NS	NS	NS
$Ca(NO_3)_2$ vs. KNO_3	NS	NS	0.036	NS

[w] Spears trimmed to 22.5 cm before weighing.
[x] NO_3-N treatments (112 kg/ha of N) and KCl and NaCl treatments (1,120 kg/ha) were broadcasted in granular form after harvest in late May 1987.
[y] Values represent the mean of four replicates averaged over the respective treatments.
[z] Contrasts generated with 1987 yield as covariates.

These findings support the recommendations of late nineteenth century agriculturalists (3,5,36,58), who were united in the opinion that rock salt was essential in asparagus production. Burr (5) and White (58) both advised applying "2 qt of coarse salt/square yard" (equivalent to 97,574 kg/ha) to asparagus beds before growth had commenced. Landreth (36) added that 20 bushels of salt to the acre could be used advantageously and would retard weeds, whereas Brill (3) proposed that five bushels per acre should be side-dressed after the third year of growth. These recommendations were supported by research that demonstrated an average 13.5% increase in yield among five asparagus varieties after application of 1,120 kg/ha (57). Other work showed that 1,120 kg of rock salt was more effective than 278 kg of $NaNO_3$ in increasing asparagus yield (45). During the 1920s, an 11-yr-old asparagus plot produced 2.1, 11.7, or 25.9% more marketable spears when NaCl was broadcast at 178, 336, or 560 kg/ha, respectively (46,47). Conversely, applying NaCl with KCl was of little value to asparagus grown on organic soils (28). Fusarium crown and root rot, however, was not a production limitation during this period from 1900 to 1940. Perhaps the increasing importance of this disease during 1950–1960 resulted from the discontinuation of the salting practice.

Over the range of NaCl and Ca/K applications described in the greenhouse study, uptake of Na^+ did not increase beyond approximately 5.5 mg/g of tissue, whereas concentrations of K^+ reached 44.4 mg/g of tissue. Asparagus fresh weights did not significantly increase with applications of K, which is consistent with previous studies (1), but fern concentrations of K^+ were correlated with plant weight ($r = 0.66$, $P = 0.019$) and with the fraction of diseased roots ($r = 0.42$, $P = 0.009$). Fern concentrations of Na^+ also were correlated with plant weights ($r = 0.80$, $P = 0.002$) and the fraction of diseased roots ($r = 0.46$, $P = 0.007$). In sugar beets, Na^+ applied at high rates will

TABLE 6. Effect of chloride salts (NaCl or KCl) and N form (NH_4NO_3 or $Ca(NO_3)_2$) on asparagus yield, Fusarium crown and root rot, tissue analyses of asparagus, and the repeated measures univariate analysis of variance for marketable yield over years (field 2)

	Marketable yield (kg)[w]				Disease rating[x]	Fern analyses (μmol/g) in 1990			
Treatment[y]	1988	1989	1990	1991	(1–3)	K^+	Na^+	Cl^-	K:Cl
NH_4NO_3	0.11	0.31	0.39	0.76	2.2[z] bc	0.37	0.01	0.09	4.2 b
NH_4NO_3 + KCl	0.15	0.20	0.21	0.56	2.6 c	0.48	0.02	0.20	2.4 a
NH_4NO_3 + NaCl	0.10	0.42	0.79	1.21	1.2 a	0.45	0.03	0.15	3.0 a
$Ca(NO_3)_2$	0.05	0.06	0.33	0.65	2.7 c	0.42	0.02	0.07	5.8 b
$Ca(NO_3)_2$ + KCl	0.09	0.27	0.55	0.83	1.4 ab	0.59	0.02	0.23	2.6 a
$CaNO_3NO_2$ + NaCl	0.07	0.23	0.36	0.56	2.0 b	0.42	0.02	0.18	2.3 a

Repeated measure univariate analysis of variance for yield

Source of variation	df	MS	F	P
N form	1	195.7	2.2	0.16
Cl	1	170.7	1.9	0.18
N form × Cl	2	441.0	4.9	0.02
Block	3	215.6	2.4	0.11
Error	15	89.4		
Years	3	2,009.3	50.1	0.00
Years × N form	3	18.0	0.5	0.72
Years × Cl	6	29.2	0.7	0.63
Years × N form × Cl	6	94.9	2.4	0.04
Years × block	9	44.8	1.1	0.37
Error	45	40.1		

[w] Plots contained five crowns; spears were cut every 2–3 days, trimmed to 22.5 cm, counted, and weighed, five times in 1988, nine times in 1989, and 12 times in 1990 and 1991.
[x] Plot vigor ratings based on the scale 1–3, where 1 = vigorous green foliage with a dense canopy; 2 = sparse foliage, but no or little signs of chlorosis or fern death; 3 = chlorotic or light green ferns accompanied with sparse, dying, or dead foliage.
[y] N treatments (56 kg/ha) and KCl and NaCl treatments (560 kg/ha) were broadcasted in granular form before and after spring harvest in 1988, 1989, 1990, and 1991.
[z] Values followed by different letters are significantly different by the modified Friedman test (9) at $P = 0.05$.

TABLE 7. Effect of NaCl on growth, Fusarium crown and root rot, and tissue analyses of two asparagus cultivars (field 3)

Cultivar	NaCl[v]	Stand count[w]	Plot rating[w]	Root[x]		Tissue analyses (μmol/g)				
				FDR	cfu/cm	K^+	Na^+	Ca^{+2}	Cl	K:Cl
Mary Washington	−	12.7[y]	2.9	0.3	0.52	0.44	0.02	0.11	0.03	14.7
	+	13.7	1.1	0.2	0.31	0.60	0.03	0.07	0.20	3.0
Syn 4-56	−	10.6	2.4	0.2	0.13	0.41	0.02	0.07	0.03	13.7
	+	10.4	1.7	0.3	0.11	0.37	0.02	0.13	0.16	2.3
Contrast (P)[z]										
Cultivar		NS	NS	NS	0.02	NS	NS	NS	NS	NS
NaCl vs. no NaCl		NS	0.005	NS	0.05	NS	NS	NS	0.001	0.001

[v] NaCl applied at 560 kg/ha in July 1989 and 1990.

[w] Stand counts refer to number of stalks per crown; plot vigor ratings are based on the scale 1–3, where 1 = vigorous green foliage with a dense canopy, 2 = sparse foliage, but no or little signs of chlorosis or fern death, 3 = chlorotic or light green ferns accompanied with sparse, dying, or dead foliage.

[x] Roots were obtained from four soils samples removed with a soil auger (22.5 × 2.0 cm diameter) per replicate plot; cfu/cm = colony-forming units of *Fusarium* spp. per centimeter of root; FDR = fraction of diseased roots determined from the length (cm) of discolored roots/total root length. Root lengths were estimated by the modified line-intersect method (55).

[y] Values represent the mean of three plots 1.2 m long (three crowns per plots).

[z] Contrasts computed using rank transformation with Kruskal-Wallis test (9).

replace K^+ in certain physiological functions (41) and increase the photosynthetic efficiency of the plant (14). In the present greenhouse study, there was a slight indication that Na^+ replaced K^+ at the higher rates, but the physiological role of Na^+ in growth and disease suppression of asparagus is unclear. Future studies should specifically examine different forms of Na on asparagus growth and disease suppression.

Fern concentrations of Cl^- surpassed those of many other macronutrients (a phenomenon not uncommon for asparagus [22] or for other crops [39]) and was well correlated with plant weights ($r = 0.71$, $P = 0.001$) and the fraction of diseased roots ($r = 0.68$, $P = 0.001$). Chloride has been implicated many times in disease suppression. For example, NH_4Cl applications decreased the severity of take-all root rot of wheat and increased yields, whereas applications of $(NH_4)_2SO_4$ were conducive to crop loss caused by take-all (54). Yields of spring wheat affected by take-all increased when chlorides were combined with NH_4OH or $CO(NH_2)_2$ amendments (20). Chloride fertilizers have increased yields of winter wheat affected by other root (19) and foliar diseases (27,48). In other studies KCl reduced the severity of soybean cyst nematode (37), Fusarium stalk rot of corn (60), common root rot of barley (23,51), and Fusarium yellows of celery (49) more than other potassium fertilizers.

The process by which inorganic ions affect disease resistance is obviously complicated. Past work has established trends between plant disease and N forms (30), K^+ (31,56), and Ca^{2+} (6,10); however, few studies have tested proposed mechanisms. In studies with wheat, application of chloride salts lowered the water potential of the roots, which was suggested to have retarded the infection process by *Gaeumannomyces graminis* (Sacc.) Arx & D. Olivier (7). The use of chloride salts in the suppression of take-all disease also has been associated with inhibiting soil nitrification, reducing uptake of NO_3-N (30), and influencing the availability or function of manganese in the rhizosphere and roots (32). Additionally, the processes that maintain charge balance within a cell may be altered by ion uptake (49,50). For example, an influx of cations, such as NH_4^+, K^+, and Ca^{2+}, into a plant cell required neutralization either by exporting H^+, importing OH^- or HCO_3^-, or synthesizing organic acids such as malate (43). Root cells can synthesize malate in large quantities; however, malate synthesis is inhibited if Cl is present (43). Theoretically, cells contain less malate if electrical neutrality is obtained with Cl nutrition. Celery plants with low K:Cl ratios in the petioles produced root exudates that contained significantly fewer organic substrates, such as malate, than plants with higher petiole ratios of K:Cl (50). Preliminary work on asparagus also indicated that NaCl reduces malate synthesis in the roots (17).

In the present study, high K:Cl ratios were associated with greater disease. Although Na^+ and Cl^- were applied stochimetrically, the Na:Cl ratios in the tissue were less correlated with the fraction of root disease or the cfu/cm of root than the K:Cl ratio. In the field, plots with less disease and increased yield and vigor were most often associated with asparagus plants containing fern K:Cl ratios between 2 and 3; ratios less than 2 were rare. The linear relationship between the K:Cl ratio and disease in the greenhouse studies may suggest that the balance between these ions play an important role in host susceptibility. These findings are similar to those with celery (49,50) and may indicate a similar effect between root exudation and NaCl nutrition in asparagus. Since the rates of NaCl used were not fungicidal or herbicidal, it may be that NaCl influences the susceptibility of the host. Since populations of *Fusarium* spp. were lower in the rhizospheres of NaCl-treated plants than in untreated plants or in fallow soil, NaCl nutrition may affect root exudation and infection. Alternately, NaCl also may be fungistatic to the pathogens and/or suppress sporulation. Additional research may demonstrate a fundamental approach for disease management in salt-tolerant crops.

The damaging effects of soil salinity caused by NaCl on crop growth including asparagus (22) has been reviewed (25,44), but few reports show growth enhancement and disease suppression with NaCl. The major difference between the present study and another (22) is that soil salinity was prevented in the present study by postapplication irrigation. Furthermore, field applications of NaCl were not continual, but applied once or twice per year. Single applications of NaCl have increased yields in other plants (14,28). The superiority of NaCl over KCl in disease suppression also could be due to the perennial nature of asparagus and to its ability to absorb and retain K, thereby not requiring additional applications of K. If this is true, it is possible that other chloride salts, such as NH_4Cl and $CaCl_2$, could suppress Fusarium crown and root rot of asparagus.

The response of other asparagus diseases to NaCl is unknown. Brief exposures of roots of some plants to saline solutions can increase their susceptibility to *Phytophthora* spp. (2,40), so NaCl applications may be counterproductive when Phytophthora root rot of asparagus (21) is present. In these studies, however, suppression of Fusarium crown and root rot and yield increases were obtained with annual rates of 560–1,120 kg/ha of NaCl. Because fern vigor in the summer is directly proportional to the crop yield the next spring (15), tissue analyses conducted after the spring cuttings could identify plantings with high K:Cl ratios that may benefit from NaCl applications. Although NaCl can be destructive to soil structure, and repeated applications may increase soil impermeability, no detectable differences in bulk density were observed in these experiments (W. H. Elmer, *unpublished data*). Sufficient irrigation after NaCl applications may be adequate to counter soil sodicity (4).

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