Effect of Low Soil pH on Aluminum Availability and on Mortality of Cherry Seedlings

H. Melakeberhan, Assistant Professor, Department of Entomology; **A. L. Jones,** Professor, Department of Botany and Plant Pathology and the Pesticide Research Center; **E. Hanson,** Associate Professor, Department of Horticulture; and **G. W. Bird,** Professor, Department of Entomology, Michigan State University, East Lansing 48824

ABSTRACT

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Levels of Al in leaf samples from 250 cherry orchards and the relationship between soil pH and Al levels in soil, roots and stems, and growth of 16-year-old sweet cherry (*Prunus avium*) trees and 1-year-old mazzard cherry seedlings were investigated. Leaf samples from commercial orchards contained 21 to 500 μg of Al per g of dry weight. Soil pH in the sweet cherry orchard was as much as 3 pH units below the recommended range (6.5 to 7.0) for optimal growth, with the concentration of available Al increasing from approximately 0.1 to 2.4 meq per 100 g with decreasing pH below pH 5.5. Levels of Al in the root system were proportional to its availability in the soil. Levels of Mg and Ca in roots decreased while Mn and Zn increased significantly ($P \leq 0.05$) with increasing Al concentrations. Changes in the concentrations of P, K, Fe, Cu, and B were not significant. Soil pH (3.9, 4.7, and 7.0) and Al levels (0 to 27 meq of Al per 100 g) observed in the field were simulated by applying aluminum chloride to potted seedlings in three greenhouse experiments. Seedlings receiving calcium chloride served as controls (experiment 4). All seedlings planted in soil below pH 4.7 died within 4 weeks, with or without Al or Cl treatment, and seedling mortality increased as Al treatment increased. Root ($P \leq 0.05$) and plant growth in general decreased with decreasing pH. Increasing Al treatment had little effect on root growth at pH 3.9 and pH 4.7 (at which little growth took place). At pH 7.0, however, root growth was reduced ($P \leq 0.05$) compared with the controls. The level of Al applied to the soil and the concentration of Al in stems of cherry seedlings was highly correlated ($P \leq 0.001$). The concentrations of macro elements in the stem ($P \leq 0.05$ to 0.001) and Mn and Zn increased ($P \leq 0.001$) with increasing Al concentrations. The interaction effect between the level of Al applied to the soil and soil pH on seedling mortality was highly significant ($P \leq 0.001$). While there was a significant interaction between soil pH and the level of Cl applied to the soil, the level of available Ca did not increase over treatments that received Al. Overall, the data suggest that low soil pH could result in seedling death in part by increasing the absorption of Al into plants to toxic levels.

Preventive and/or therapeutic means of plant disease management depend on how well the phenomena and the intra- and inter-associations of the possible cause and effect relationships are established. Management is particularly difficult when causes of a disease are complex. The case of *Prunus* spp. decline in North America, caused by biotic (mostly nematodes and *Pseudomonas* spp.) and abiotic (low soil pH, nutritional imbalance, and winter injury) (5,11,21–23), is one example. Although the causes for decline vary greatly with geographic regions, low soil pH appears to be a common factor associated with orchards with declining stone fruit trees in the southeastern (5) and northeastern U.S. (11), and in Michigan (21). The mechanism by which soil pH affects tree health in the decline phenomena is not understood.

Corresponding author: H. Melakeberhan
E-mail: melakebe@pilot.msu.edu

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The optimum soil pH for growth of sweet cherry trees is 6.5 to 7.0 (7); otherwise, nutritional imbalances, deficiencies, and toxicities are unavoidable (4). As pH decreases below 5.5, there is an increase in the availability of aluminum and the potential for aluminum toxicity (10,15,18), and for deficiencies of calcium and other major elements (8,14,25). These changes result in a domino effect of nutritional deficiency, overall physiological disturbance, and early senescence (10,13). This process may weaken trees and predispose them to infectious diseases and various environmental stresses. For example, the incidence of bacterial canker increases with decreasing soil pH (20,26,27).

An average pH of 5.1 was reported for five Michigan sweet cherry orchards with varying degrees of decline (21). One of these orchards (orchard 1), had 30.5% tree mortality and leaf Al concentrations of 392 μg per g of dry weight. The high Al concentrations were similar to those reported in declining peach orchards in the southeastern U.S. (14,25) and to levels experimentally shown to be toxic to other *Prunus* spp. (6,8,9), and well above the average of 132 μg/g (from 1,809 samples) for Michigan cherry orchards. The combination of low soil pH and high leaf Al concentrations and high tree mortality in orchard 1 led to the hypothesis that low soil pH may contribute to the decline of sweet cherry trees in Michigan.

The objectives of this study were to determine (i) the range of leaf Al concentrations present in Michigan cherry orchards, (ii) the correlation between soil pH and the availability of Al in a declining sweet cherry orchard, and (iii) the response of mazzard cherry seedlings to soil pH and Al ranges observed under orchard conditions.

MATERIALS AND METHODS

Aluminum in leaf samples from a statewide survey. From 1986 through 1991, the Soil Testing Laboratory at Michigan State University analyzed 1,412 leaf samples (36 to 92 per year) from over 250 sweet and sour cherry orchards in 11 counties throughout Michigan. Several orchards were sampled twice during the 5-year period. Leaf samples (1 to 20 per orchard) were collected from mid July to late August from the middle of the current season's shoot growth, dried at 65°C, ground in a Wiley mill using a 60-mesh screen, and ashed in a muffle furnace at 500°C. Ash samples were dissolved in 3 N nitric acid, then analyzed for Al with an inductively coupled plasma emission spectrophotometer (Beckman Instruments, Fullerton, Calif.) (16). Data were arbitrarily grouped into four ranges. The number of samples in each category was expressed as a percentage of the total number of samples.

Soil pH and soil and root aluminum in a declining sweet cherry orchard. Twelve 16-year-old sweet cherry trees of the cultivar Bing (orchard 1) (21) on mazzard rootstock were selected to examine the relationship of tree health and of available Al in the rhizosphere soil and root system with soil pH. Tree health was assessed as follows: 0 = high vigor and no cankers on lateral or scaffold branches; 1 = moderate vigor, cankers on lateral branches, and reduced shoot growth; and 2 = low vigor, cankers on scaffold branches, and dieback of shoots and branches.

On 12 November 1991, a backhoe was used to dig a trench about 3 m long by 1 m wide by 1.5 m deep along the west side of each tree about 0.5 m from the trunk. A 2.4 m wide (1.2 m on each north and south side from the trunk) by 0.8 m deep area of the trench surface closest to each tree was measured off for sampling (Fig. 1). A total of 216 soil samples, each of approximately 500 cm^3, were collected from each tree. Soil samples were collected from a 40-cm-wide by 20-cm-deep area in the top 40 cm of each trench and from a 40 by 40 cm area in the lower 40 cm of each trench. A total of 24 root (one from each side of a tree) samples were collected from the top 40 cm and 21 root samples from the bottom 40 cm of the soil trench. Each sample consisted of 10 to 15 g of root tissue.

Soil pH and available soil Al were determined, using inductively coupled plasma optical emission spectroscopy on filtrates of a 5-g subsample dissolved in 50 ml of 1 N KCl (2), by the Michigan State University Animal Health Diagnostic and Toxicology Laboratory. Other changes possibly associated with soil pH and availability of Al were not determined. Root samples were analyzed for P, K, Mg, Ca, Fe, Mn, Cu, Zn, B, and Al by the Michigan State University Soil Testing Laboratory (16). Relationships among tree health (as defined above), soil pH, available soil Al, and the levels of various elements in roots were analyzed by regression and analysis of variance (SAS Statistics, release 6.03 ed., SAS Institute, Cary, N.C.). Means for tree health and soil horizon were separated by Tukey's HSD test (SAS). Unless differences were observed by either lateral or vertical distribution or by tree health category, data for each parameter were combined.

Greenhouse studies. Previously, pH values of 3.5 to neutrality were detected in Michigan sweet cherry orchards (21). Therefore, pH levels of 3.9 (low), 4.7 (medium), and 7.0 (neutral) were tested in all greenhouse experiments. A sandy loam soil (similar to the type found in orchard 1) was obtained from a continuous rye field site at the Michigan State University campus and steam sterilized. Soil pH was adjusted by mixing the sterilized soil with 90% elemental sulfur powder at 0 to 0.7% by weight (12) for 3 min in a cement mixer, and stored in plastic barrels. Soil pH was checked every 2 weeks for 3 months using a portable pH and soil moisture tester (O.S.K.E.M. System Soil Tester, Tokyo, Japan) and then analyzed by the Michigan State University Soil Testing Laboratory.

The impracticality of determining all of the complex physiochemical changes that took place under orchard conditions and logistics forced us to assume that similar pH ranges of similar soil types will have similar physiochemical conditions. Furthermore, there is no form of Al that could be applied by itself. Therefore, Al was used as aluminum chloride and calcium chloride was used as a control. Al dose selection was dependent on field observations and that of Cl, in part, on what the normal ranges were for a similar soil type (4). When applied as calcium chloride, the upper range of Cl carried about the middle ranges for Ca for the type of soil (4) used in the experiments described here. No attempt was made to apply Ca in other forms.

Three factorial experiments (experiments 1, 2, and 3) with four to five levels of aluminum and one experiment (experiment 4, control) with six levels of chloride were conducted at the three pH levels in a

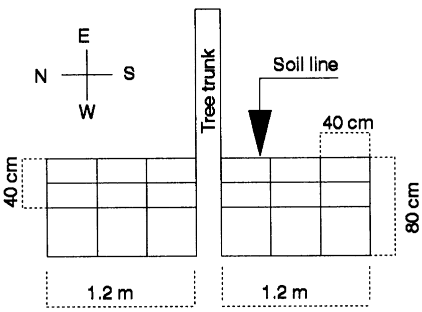

Fig. 1. Diagrammatic representation of the area where soil and root samples were collected for pH and Al analysis from 2.4-m-long by 80-cm-deep trenches dug about 0.5 m from the trunk of 12 sweet cherry trees in orchard 1. Soil samples were collected from each rectangle and root samples across the top 0 to 40 cm and bottom 41 to 80 cm of each 2.4-m-long trench.

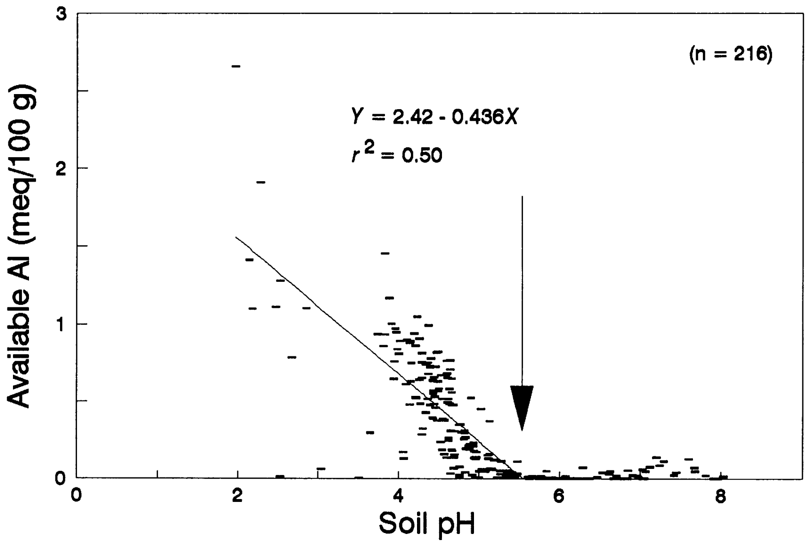

Fig. 2. Relationship between soil pH and available soil Al for 216 samples taken from 12 sweet cherry trees in orchard 1. Arrow indicates the average soil pH observed in five Michigan orchards (21). The regression line indicates the sharp increase in Al availability as soil pH declines below pH 5.5 (for r^2, $P < 0.05$).

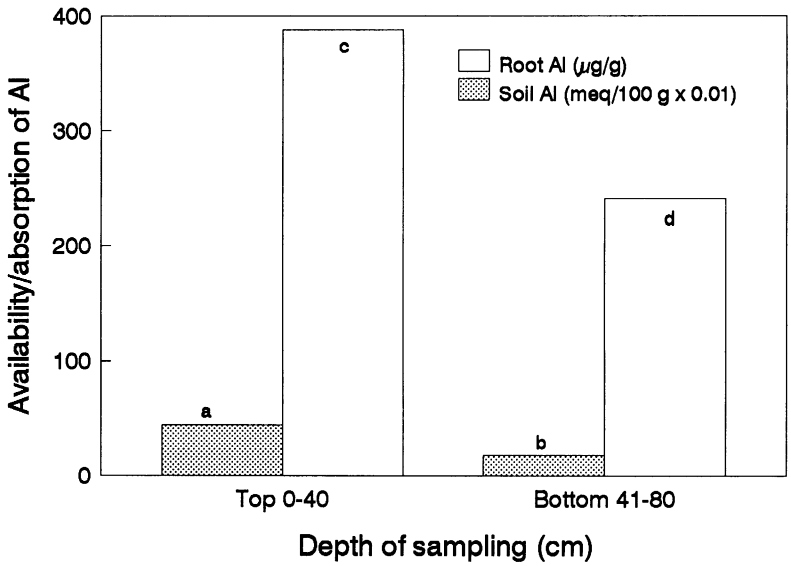

Fig. 3. Relationship between availability of Al in soil and absorption into cherry root system in the top 0 to 40 cm and bottom 41 to 80 cm of soil around 12 trees in orchard 1. Bars with the same shading followed by different letters are significantly different from each other.

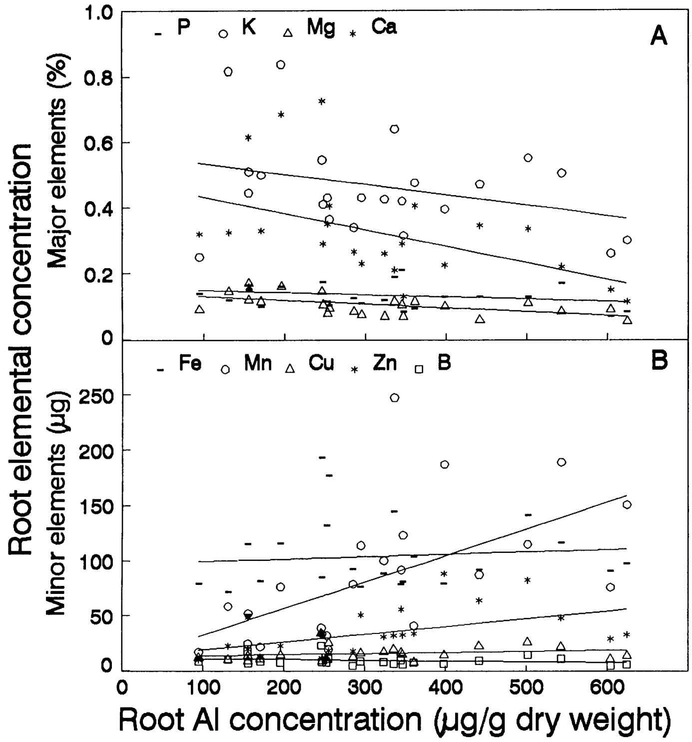

Fig. 4. Relationship between the concentrations of Al and **(A)** macro and **(B)** micro elements in roots from 12 sweet cherry trees taken from orchard 1. Y values for each element were: P = 0.152 – 0.000064X, r^2 = 0.07; K = 0.563 – 0.00032X, r^2 = 0.10; Mg = 0.139 – 0.00011X, r^2 = 0.30*; Ca = 0.48 – 0.0005X, r^2 = 0.21*; Fe = 97.5 + 0.02X, r^2 = 0.01; Mn = 8.37 + 0.24X, r^2 = 0.34*; Cu = 12.5 + 0.01X, r^2 = 0.06; Zn = 11.9 + 0.07X, r^2 = 0.25*; B = 11.3 – 0.006X, $r2$ = 0.05. * = significant difference at P < 0.05 according to Tukey's HSD test.

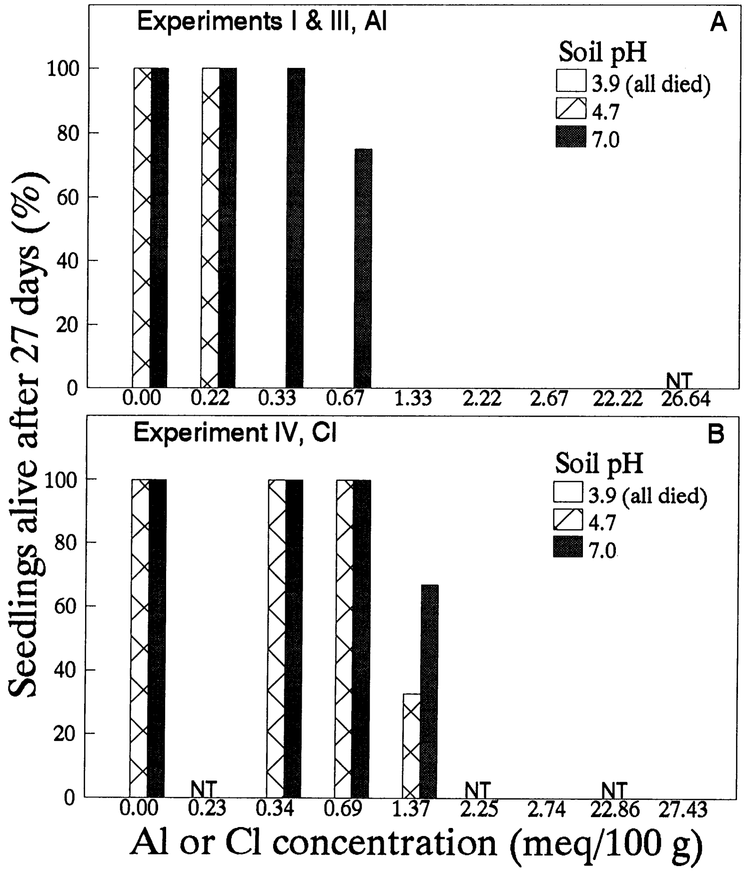

Fig. 5. Mazzard cherry seedlings alive 27 days after planting in soil adjusted to pH 3.9, 4.7, or 7.0 and treatment with increasing levels of **(A)** aluminum or **(B)** chloride. NT = treatment not tested. Mortality was 100% at pH 3.9 regardless of Al or Cl treatment.

greenhouse maintained at 25 ± 2°C. Experiments 1, 2, and 3 were replicated four times and experiment 4 three times. All experiments were conducted on 1-year-old *Prunus avium* L. mazzard seedlings, individually planted in 800 cm^3 (equal to approximately 944 g of fresh weight) of soil in 20-cm-deep and 8-cm-diameter black plastic tubes. Mazzard seedlings were obtained from Meadow Lake Nursery, McMinnville, Oreg., and stored at 4.5 ± 1°C for approximately 1,200 h until budbreak commenced. Seedlings were kept under laboratory conditions (about 20 ± 2°C) with roots submerged in buckets containing tap water for 24 h. Afterwards, seedlings were selected for growth uniformity and transplanted.

In experiments 1 and 2, seedlings at each pH level received 0, 0.22, 2.22, or 22.22 meq Al per 100 g of soil; in experiment 3, they received 0, 0.33, 0.67, 1.33, or 2.66 meq Al per 100 g of soil. In experiments 1 and 3, the total amount of aluminum chloride needed for each treatment was dissolved in 480 ml of tap water and 40 ml of the solution was applied to each seedling in one application. In experiment 2, the total amount of aluminum chloride was dissolved in 4.8 liters of tap water and applied in approximately 30-ml aliquots every other day over a 2-week period. In experiment 4, seedlings at each pH level received 0, 0.34, 0.69, 1.37, 2.74, or 27.43 meq Cl per 100 g of soil in aliquots of 40 ml in one application. The levels of Al were representative of the ranges of concentrations observed in orchard soils (21), whereas the levels of Cl were representative levels of Cl applied with Al in experiments 1 through 3. With the exception of the 27.42 meq of Cl per 100 g treatment, the levels of Ca applied in experiment 4 did not exceed Ca levels that occur naturally in sandy loam soils (4). All Al and Cl treatments were initiated 4 ± 1 days after transplanting and each experiment lasted for 27 ± 1 days. The seedlings were watered daily with tap water and fertilized twice a week with Peters (Grace Sierra, Milpitas, Calif.) general purpose fertilizer mix.

Observations and measurements. Occurrences of leaf scorching, wilting, and seedling death were recorded during the course of each experiment. A seedling was considered dead when all of the leaves turned brown and the shoot system collapsed. At the end of each experiment, shoots and roots were dried separately and their weights recorded. Stems collected from seedlings in experiment 3 were analyzed for P, K, Mg, Ca, Fe, Mn, Cu, Zn, B, and Al (16). Soil pH and Ca concentrations were determined for each experiment at the end of the study. Main treatment effects of Al, Cl, and pH, and interaction effects of Al × pH and Cl × pH were analyzed by experiment and by treatments using General Linear Models (SAS).

RESULTS

Aluminum in leaf samples from a statewide survey. The concentration of Al in the 1,412 leaf samples from Michigan cherry orchards varied from 21 to 500 µg Al per g of dry weight. About 39% of the samples had 21 to 100, 42% had 101 to 200, 14% had 201 to 300, and 5% had 301 to 500 µg of Al per g of dry leaf weight.

Soil pH and soil and root aluminum in a declining sweet cherry orchard. Three trees were rated high in vigor, four trees moderate in vigor, and five trees low in vigor. The top 40 cm of the orchard soil was sandy loam and the bottom 41 to 80 cm was sand. Soil pH averaged 5.13 but ranged from 2 to 8. There was no statistical difference in soil pH due to lateral distance of sampling from the base of the trunk or tree health category. However, the average pH (4.92) for all samples taken from the top 40 cm was significantly lower ($P \leq 0.05$) than the pH (5.34) from samples taken from the bottom 41 to 80 cm.

Available Al ranged from 0 to 2.65 meq per 100 g of soil and below pH 5.5 the amount of available Al increased proportionally with decreasing pH (Fig. 2). There was significantly ($P \leq 0.05$) more available Al in soil samples collected from the top 40 cm of soil than from samples collected from the bottom 41 to 80 cm of soil (Fig. 3). Concentrations of Ca and Mg in roots decreased ($P \leq 0.05$) whereas Mn and Zn increased ($P \leq 0.05$) with increasing Al in the roots (Fig. 4). Levels of K, P, Cu, and B did not change significantly with increasing Al in the roots.

Greenhouse studies. Within 7 days after treatment, seedlings planted into soil at pH 3.9, in soils treated with 27.43 meq of Cl per 100 g, and in all soils treated with more than 2 meq of Al per 100 g, exhibited leaf burning and scorching, starting with the youngest leaves, followed by wilting and dieback of the shoots. There was no difference in symptom development in plants treated with a single or split applications of Al above 2 meq per 100 g. Below 2 meq of Al per 100 g, seedling mortality began about 7 days earlier in single than in split application treatments.

When seedlings were planted in soils at pH 4.7 and 7.0, the response varied depending on the concentration of Al or Cl that was applied to the soil (Fig. 5). At pH 4.7, Al concentrations above 0.22 meq per 100 g resulted in 100% seedling mortality, whereas, at pH 7.0, Al concentrations above 0.67 meq per 100 g resulted in 100% seedling mortality (Fig. 5A). When calcium chloride was applied in place of aluminum chloride, 66 and 33% seedling mortality was observed at initial soil pHs of 4.7 and 7.0, respectively, when the Cl concentration was 1.37 meq per 100 g (Fig. 5B). Above 1.37 meq per 100 g, chloride was toxic irrespective of soil pH (Fig. 5B). Greater seedling mortality was observed among seedlings planted in soil adjusted to pH 4.7 than in soil adjusted to pH 7.0 (Fig. 5).

Root weight did not change significantly at pH 3.9 and 4.7 while it decreased ($P \leq 0.05$) at pH 7.0 with increasing Al treatment (Fig. 6A). Root weight, however, significantly decreased with decreasing soil pH (Fig. 6B). Differences in dry

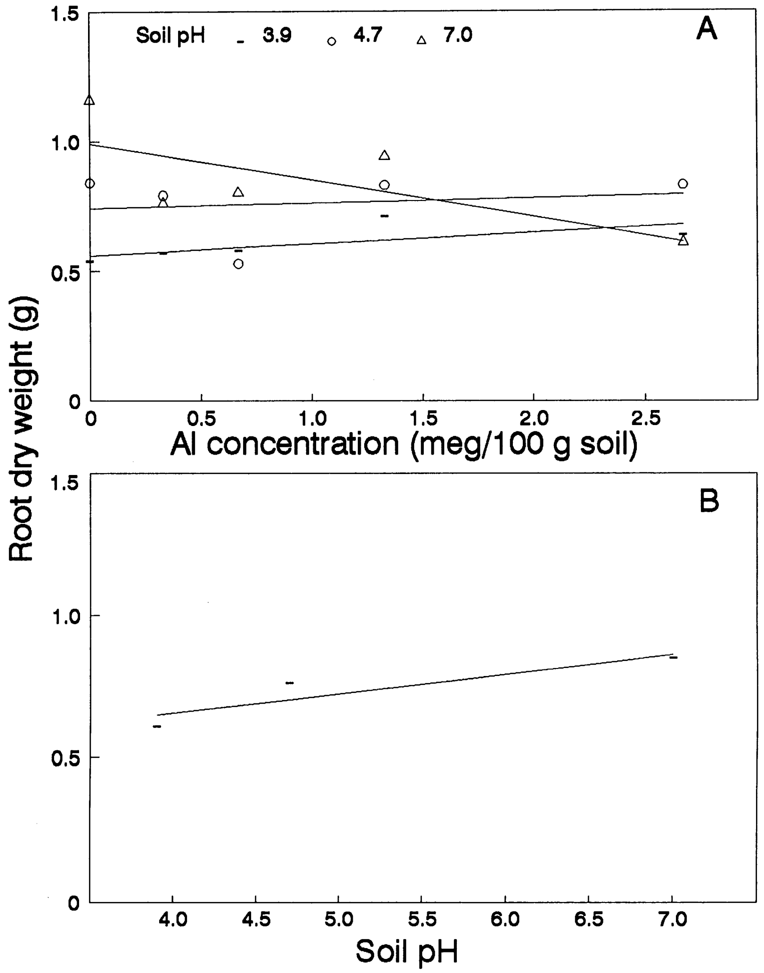

Fig. 6. Effect of **(A)** increasing Al treatment and **(B)** decreasing soil pH on root growth. **(A)** Y values for Al treatment are: pH 3.9 = 0.562 + 0.044X, r^2 = 0.03; pH 4.7 = 0.74 + 0.02X, r^2 = 0.04; pH 7.0 = 0.99 + 0.14X, r^2 = 0.29*. **(B)** Y = 0.376 + 0.07X, r^2 = 0.10*. * = significant difference at $P < 0.05$ according to Tukey's HSD test.

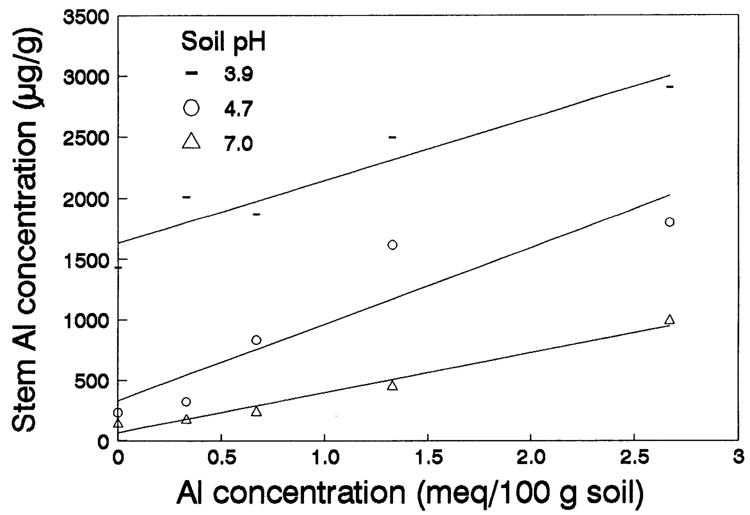

Fig. 7. Relationship between Al treatment in soil and the concentration of Al in stems of mazzard seedlings 27 days after treatment at pH 3.9, 4.7, and 7.0. Y values are: pH 3.9 = 1632.4 + 511.2X, r^2 = 0.39**; pH 4.7 = 329.5 + 632.8X, r^2 = 0.74***; pH 7.0 = 66.5 + 330.4X, r^2 = 0.39**. ** and *** = significant differences at $P < 0.01$ and 0.001, respectively, according to Tukey's HSD test.

weights due to treatment were not significantly different from Al or Cl treatments, but in experiments 3 and 4 dry weights tended to decrease with decreasing soil pH (Table 1). In each experiment, low soil pH and increasing Al and Cl treatments significantly ($P \leq 0.05$ to 0.001) affected the number of healthy leaves present at the end of 27 days (Table 1). The interactions of Al × pH in affecting plant dry weight (experiment 3), and Al × pH (experiments 2 and 3) and Cl × pH (experiment 4) in affecting the number of healthy leaves were significant (Table 1). Soil pH generally decreased with increasing Al or Cl treatment but the magnitude was much higher in Al than in Cl treatment (Table 2). Calcium chloride appeared to increase Ca whereas Al treatment significantly ($P \leq 0.05$ to 0.001) decreased soil Ca in all experiments (Table 2). Soil pH was significantly affected by the interaction of Al × pH and Cl × pH ($P \leq 0.05$ to 0.001) and soil Ca by Al × pH (experiment 3) (Table 2).

Table 1. Regression equations of main effects of various concentrations of Al or Cl applied to soils adjusted to three pH levels and interaction effects of Al × pH and Cl × pH on the growth of mazzard cherry seedlings 27 days after treatment

	Al or Cl treatment[a]			pH treatment[b]		
Experiment	Equations (Y)	r^2	P	Equations (Y)	r^2	P
Main effects						
1	2.71 – (0.020Al)[c]	0.04	NS[d]	1.71 + (0.168pH)[c]	0.07	NS
2	2.82 – (0.029Al)[c]	0.07	NS	1.46 + (0.226pH)[c]	0.08	NS
3	1.78 – (0.115Al)[c]	0.04	NS	0.95 + (0.136pH)[c]	0.10	*
4	2.29 – (0.024Cl)[c]	0.07	NS	0.69 + (0.281pH)[c]	0.16	*
1	10.41 – (0.51Al)[e]	0.20	***	–07.61 + (2.86pH)[e]	0.12	*
2	12.26 – (0.60Al)[e]	0.20	***	–11.59 + (3.88pH)[e]	0.16	**
3	07.04 – (3.39Al)[e]	0.22	***	–08.75 + (2.38pH)[e]	0.21	***
4	11.04 – (0.43Cl)[e]	0.16	**	–10.3 + (3.65pH)[e]	0.21	***
Interaction effects (Al × pH and Cl × pH)[f]						
1	1.83 – (0.019Al) + (0.169pH) – (0.0001Al × pH)[c]				0.10	NS
2	0.96 + (0.081Al) + (0.356pH) – (0.0211Al × pH)[c]				0.20	NS
3	0.33 + (0.626Al) + (0.279pH) – (0.143Al × pH)[c]				0.23	*
4	0.45 + (0.044Cl) + (0.353pH) – (0.0132Cl × pH)[c]				0.26	NS
1	–10.9 + (0.53Al) + (4.1pH) – (0.20Al × pH)[g]				0.37	NS
2	–16.6 + (0.81Al) + (5.5pH) – (0.27Al × pH)[g]				0.42	*
3	–15.4 + (6.68Al) + (4.3pH) – (1.94A × pH)[g]				0.55	***
4	–13.1 + (0.51Cl) + (4.6pH) – (0.18Cl × pH)[g]				0.42	*

[a] Al treatments were 0, 0.22, 2.22, and 22.22 in experiments 1 and 2, and 0, 0.33, 0.67, 1.33, and 2.67 meq per 100 g in experiment 3; Cl treatments were 0, 0.34, 0.69, 1.37, 2.74, and 27.43 meq per 100 g (experiment 4).
[b] Soil pH treatments were 3.9, 4.7, and 7.0 in all experiments.
[c] Y = total plant dry weight (g).
[d] NS = not significant; *, **, *** = significant differences at $P \leq 0.05$, 0.01, or 0.001, respectively, according to Tukey's HSD test.
[e] Y = number of healthy leaves per plant.
[f] $Y = b_0 + b_1\text{Al} + b_2\text{pH} + b_3\text{Al} \times \text{pH}$ where b_0 = intercept and b_1, b_2, and b_3 = slopes of changes due to effect of Al or Cl, pH, and Al × pH or Cl × pH treatments, respectively.
[g] Y = number of healthy leaves.

Table 2. Regression equations of main effects of various concentrations of Al or Cl applied to soils adjusted to three pH levels and interaction effects of Al × pH and Cl × pH on final soil pH and available soil Ca 27 days after treatment

	Al or Cl treatment[a]			pH treatment[b]		
Experiment	Equations (Y)	r^2	P	Equations (Y)	r^2	P
Main effects						
1	4.72 – (0.034Al)	0.07	NS[c]	5.16 – (0.178Al)	0.70	***
2	4.71 – (0.038Al)	0.07	NS	3.94 – (0.124Al)	0.44	***
3	4.85 – (0.344Al)	0.07	*	4.23 - (0.303Al)	0.09	*
4	5.35 – (0.0002Cl)	0.00	NS	2.54 + (0.028Cl)	0.12	**
Interaction effects (Al × pH and Cl × pH)[d]						
1	0.09 + (0.179Al) + (0.889pH) – (0.041Al × pH)[e]				0.74	***
2	–0.82 + (0.206Al) + (1.063pH) – (0.047Al × pH)[e]				0.84	***
3	–1.07 + (1.321Al) + (1.139pH) – (0.320Al × pH)[e]				0.95	***
4	–2.06 + (0.078Cl) + (1.425pH) – (0.015Cl × pH)[e]				0.96	***
1	5.84 – (0.132Al) – (0.132pH) – (0.009Al × pH)[f]				0.71	NS
2	5.57 – (0.125Al) – (0.313pH) – (0.00004Al × pH)[f]				0.50	NS
3	3.99 – (1.271Al) – (0.046pH) – (0.186Al × pH)[f]				0.26	*
4	2.04 + (0.017Cl) + (0.096pH) – (0.002Cl × pH)[f]				0.16	NS

[a] Al treatments were 0, 0.22, 2.22, and 22.22 in experiments 1 and 2, and 0, 0.33, 0.67, 1.33, and 2.67 meq per 100 g in experiment 3; Cl treatments were 0, 0.34, 0.69, 1.37, 2.74, and 27.43 meq per 100 g (experiment 4). Y = final soil pH.
[b] Soil pH treatments were 3.9, 4.7, and 7.0 in all experiments. Y = available soil Ca (meq per 100 g).
[c] NS = not significant; *, **, *** = significant differences at $P \leq 0.05$, 0.01, or 0.001, respectively, according to Tukey's HSD test.
[d] $Y = b_0 + b_1\text{Al} + b_2\text{pH} + b_3\text{Al} \times \text{pH}$ where b_0 = intercept and b_1, b_2, and b_3 = slopes of changes due to effect of Al or Cl, pH, and Al × pH or Cl × pH treatments, respectively.
[e] Y = final soil pH.
[f] Y = available soil Ca (meq per 100 g).

The concentration of Al in stems significantly ($P \leq 0.01$) increased with increasing Al treatment at all three pH levels and more so with decreasing pH (Fig. 7). The concentrations of P, K, Mg, Ca, Mn, and Zn in stems increased ($P \leq 0.001$) with increasing Al concentration, while the levels of Fe, Cu, and B did not change significantly (Fig. 8). The concentrations of Al, P, Mg, Fe, Mn, and Zn decreased with increasing soil pH (Table 3). Levels of other elements were not significantly affected. With the exception of decreasing stem Ca ($r^2 = 0.48$), there was no significant interaction between Al and pH.

DISCUSSION

The availability of Al increased with decreasing soil pH below 5.5 under orchard (Fig. 2) and greenhouse (Fig. 7, zero Al and Cl treatments) conditions. The higher the available amount of Al in the soil, the greater the concentration of Al detected in roots (Fig. 3) and stems (Fig. 7). The correlation between low soil pH and high seedling mortality (Table 1, Fig. 5) and highly significant interactions between pH and Al (Table 2) in the greenhouse studies support the hypothesis that low soil pH may contribute to a decline of sweet cherry trees in Michigan. However, the response of mature trees and seedlings in symptom expression was different. For example, mature trees exhibited varying degrees of dieback whereas seedlings exhibited marginal burning and leaf scorching within 7 days after transplanting. If one assumes that the complex soil physiochemical factors (undetermined) of a similar soil type under orchard and greenhouse conditions for the same pH ranges (e.g., below 4.7) were similar, the difference in response could be explained by the level and time of exposure to adverse conditions. Generally, younger root tissues are likely to absorb more of the nutrient elements and Al from the soil (Figs. 7 and 8) than older root tissues are (Figs. 3 and 4), thereby increasing the chances of toxicity. In the case of the actively growing seedlings, the entire root systems are suddenly exposed to the unfavorable soil environment and they are likely to be severely affected. In contrast, the mature tree root systems are exposed gradually (because growers do lime at planting) and are less likely to be severely affected.

The increased marginal burning and scorching of leaves within 7 days after the seedlings were transplanted into low soil pH and those treated with high concentrations of Al or Cl indicates that these treatments were highly toxic. It is also possible that salt toxicity (not determined) may have caused or contributed to this toxic effect. Although Cl is considered safe for plant growth at concentrations of 0.03 to 2.86 meq per 100 g (4), we began to see death of mazzard cherry seedlings at Cl concentrations above 0.69 meq per 100 g (Fig. 5B). With aluminum chloride treatment, however, similar levels of seedling death were observed at or below 0.69 meq per 100 g (Fig. 5A). While Cl may have contributed to the leaf injury symptoms, the high availability and absorption of Al (Fig. 7) and 100% seedling mortality (Fig. 5) at low pH without aluminum chloride treatment indicate that it was likely due to Al toxicity.

Although toxic levels of Al vary widely with crop and soil types (10,19) and Al is most toxic at pH levels below 5.5 (17), the relationship between tree age and susceptibility to Al toxicity is not well known. Aluminum concentrations above 0.67 meq per 100 g were highly toxic to mazzard seedlings irrespective of soil pH (Fig. 5). Seedlings died more rapidly with increasing Al treatment and with decreasing soil pH without Al treatments. This is to be expected because at about soil pH of 4.2 the concentration of available Al equilibrates at 0.67 meq of Al per 100 g (Fig. 2), which is toxic to cherry seedlings. Increased survival of seedlings at pH 7 compared with that at pH 4.7 when exposed to 0.67 meq of Al per 100 g was likely due to precipitation of Al at the higher pH (19). The inverse relationship between soil pH below 5.5 has been reported previously (1, 3,10,19), but our results clearly show the point at which further declines in soil pH increase the amount of available Al. Therefore, one of the major benefits of maintaining optimum orchard soil pH is lowering the availability of Al.

Decreased plant growth (Table 1 and Fig. 6) and the creation of nutritional imbalance in soil (Table 2), root (Fig. 5), and stem (Table 3 and Figs. 7 and 8), are some of the impacts of low pH, leading to deficiencies and toxicity (10,14,24). In the orchard study, the concentrations of the major nutrient elements in the roots decreased while the minor elements increased with increasing Al levels (Fig. 4), whereas all elements increased in the stems of mazzard seedlings (Fig. 8). We measured similar levels of all of the nutrient elements in the roots and stems, but those of Al and Mn were 10-fold higher in the seedling stems (Figs. 7 and 8) than they were in the roots in the orchard study (Figs. 3 and 4). This is a clear indication of nutritional imbalance leading to toxicity and may explain the high seedling mortality (Fig. 5). While the increase of stem nutrient concentrations over a 4-week period may indicate high uptake rate by the seedlings, the significant decrease in soil Ca with increasing Al treatment during the same period (Table 2) indicates that Al may be interfering with nutritional balance in the long run. Similar nutritional imbalances have been reported for peach (14, 25).

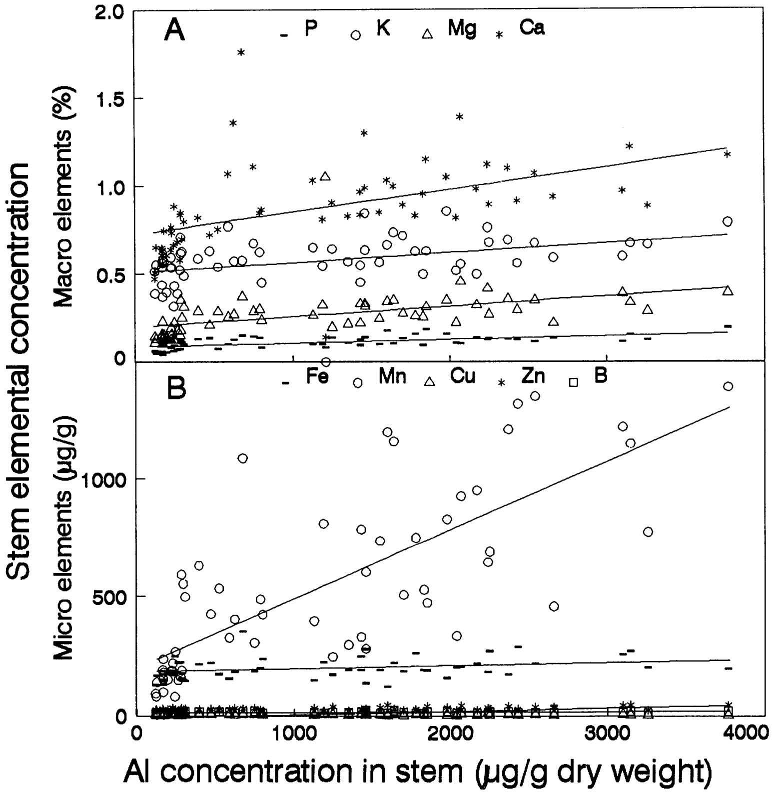

Fig. 8. Relationship between the concentrations of Al and (**A**) macro and (**B**) micro elements in stems of mazzard seedlings 27 days after treatment. Y values for each element were: P = 0.091 + 0.203X, r^2 = 0.35***; K = 0.511 + 0.56X, r^2 = 0.16*; Mg = 0.201 + 0.586X, r^2 = 0.18**; Ca = 0.73 + 1.27X, r^2 = 0.24***; Fe = 178.2 + 0.013X, r^2 = 0.07; Mn = 194.6 + 0.292X, r^2 = 0.58***; Cu = 7.7 to 0.0004X, r^2 = 0.02; Zn = 24.0 + 0.004X, r^2 = 0.34***; B = 14.0 + 0.0008X, r^2 = 0.05. *, **, and *** = significant differences at P < 0.05, 0.01, and 0.001, respectively, according to Tukey's HSD test.

The fact that there was no relationship between tree health category and soil pH or the availability of Al under orchard conditions suggests that other factors may be involved. Low soil pH is one of the factors in decline of stone fruits, and decline usually starts 6 to 8 years after planting (5). It is likely that the decline of soil pH and the accumulation of toxic levels of Al under orchard conditions may be a gradual process with increasingly detrimental impact on the newly emerging fine roots. Whether bacterial canker symptoms appear or not depends on the presence of the causal agent (*Pseudomonas syringae*). However, it has been shown that low soil pH increases stone fruit tree susceptibility to bacterial canker (26,27) and other diseases (20).

Soil pH of all of the cherry orchards where the leaf samples were collected in Michigan is not known. However, 81% of the samples contained 21 to 200 µg of Al per gram of dry leaf weight. About 5% of the leaf samples from cherry trees in Michigan were at or above the 300 µg of Al per g of dry weight found in leaves from orchard 1 (21), which was either similar to or lower than concentrations associated with the decline in peach trees (14) or the susceptibility to peach tree short life in the

Table 3. Linear regression of the effect of soil pH on various elements in stems of 1-year-old mazzard cherry seedlings at 27 days after treatment[a]

Elements	Equations (Y)	r^2	P
Al	3,740 – (494pH)	0.45	***[b]
P	1,692 – (104pH)	0.17	**
K	6,852 – (190pH)	0.05	NS
Mg	4,363 – (346pH)	0.29	***
Ca	10,904 – (388pH)	0.05	NS
Fe	251 – (11pH)	0.09	*
Mn	1,480 – (181pH)	0.42	***
Cu	2.63 + (1.11pH)	0.02	NS
Zn	39 – (1.90pH)	0.13	**
B	18 – (0.52pH)	0.05	NS

[a] Data are from experiment 3 and soil pH treatments were 3.9, 4.7, and 7.0.

[b] NS = not significant; *, **, *** = significant differences at $P \leq 0.05$, 0.01, or 0.001, respectively, according to Tukey's HSD test.

southeastern U.S. (25). Although the high ranges of Al concentrations have been shown to be toxic to peach seedlings (6,8, 9), we still do not know what levels of Al are toxic to mature cherry trees. Nonetheless, the high Al concentrations in soil, root, stem, and leaf samples indicate that more attention should be paid to soil pH.

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