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Cadmium Uptake by Cucumber from Soil Amended with Phosphorus Fertilizers

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ABSTRACT. **Cadmium (Cd) concentrations in some phosphorus (P) fertilizers may be high enough to cause significant Cd accumulation in plants. A 2-year field experiment was conducted on a Sultan silt loam (Aquandic Xerochrept) to determine how the availability to cucumber (*Cucumis sativus* L.) of Cd from a triple superphosphate (TSP) and a western phosphate rock (PR) was affected by rate of Cd input and liming. A water-soluble Cd salt, $CdCl_2$, was included for comparison. Cucumber vine growth increased with increasing TSP application rates but was unaffected by the application of PR or $CdCl_2$. Cucumber fruit yield, however, was unaffected by the application of either P fertilizer or $CdCl_2$. Concentrations of Cd in cucumber vine or fruit responded to increased Cd inputs from PR, TSP, or $CdCl_2$, and the vine was the primary sink for Cd that accumulated in the plant. Both vine and fruit Cd correlated better with soil total Cd than with labile Cd extractable by 0.05 M $CaCl_2$ or DTPA (diethylenetriaminepentaacetic acid). A unique characteristic of cucumber vine- or fruit-Cd is that it was unaffected ($P > 0.05$) by lime rate and Cd source and not closely related to labile or exchangeable Cd as measured by 0.05 M $CaCl_2$, in contrast to previous findings for other vegetable or grain crops. Root exudates could have controlled the solubility of Cd in the soil. The low availability of Cd from these sources to the plant was evidenced by the low uptake coefficient of Cd (0.461 to 1.059) from the soil to the cucumber fruit and low Cd recovery (0.43%) in both vine and fruit of Cd added.**

Cadmium (Cd) is one of the heavy metals potentially harmful to human health. It is readily available to plants and is not phytotoxic even at concentrations in crops that can increase human exposure to levels that cause health concerns (Adriano, 1986). Land disposal of municipal and industrial wastes that are used for their fertility benefits is an important pathway for the entry of Cd into soil (Wilson, 2001). Another pathway is the application of fertilizers for crop production. This is because some commercial phosphorus and trace element fertilizers contain elevated concentrations of Cd and other heavy metals (Mortvedt et al., 1981; Raven and Loeppert, 1997; Williams and David, 1973). Since only a small portion of the Cd added is removed by the crop, repeated applications of the fertilizers produce Cd input rates higher than the crop removal, which may lead to Cd accumulation in the soil (Nicholson and Jones, 1994). As a result, there are concerns as to the environmental and health risk from continued use of such fertilizers (McLaughlin et al., 1996).

Several studies have revealed a high availability of Cd in P fertilizers to plants. Reuss et al. (1978) found that the application of triple superphosphate (TSP) increased Cd accumulation in radish (*Raphanus sativus* L.), lettuce (*Latuca sativa* L.), and peas (*Pisum sativum* L.). Other investigators also found a significant increase in Cd uptake by grain and vegetable crops following additions of NPK fertilizers to soil (He and Singh, 1994; Grant and Bailey, 1998; Guttormsen et al., 1995). However, there are also findings contradicting these results. Mortvedt et al. (1981) and Mortvedt (1985) showed no significant increase in Cd concentrations in winter wheat (*Triticum aestivum* L.) or immature corn (*Zea mays* L.) with normal application rates of TSP containing Cd up to 153 $mg \cdot kg^{-1}$ or of Zn fertilizers containing Cd up to 2165 $mg \cdot kg^{-1}$. Whether or not application of a fertilizer will lead to an increase in plant accumulation of Cd may hinge upon factors including input rates of Cd from fertilizers, its solubility, and type of plant species involved (Grant et al., 1998).

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Most studies that examined the availability to crops of Cd from fertilizers focus on grain (Grant and Bailey, 1998; Mortvedt et al., 1981; Mortvedt, 1985; Mortvedt, 1987; Mulla et al., 1980) and leafy vegetable crops (He and Singh, 1994; Kim et al., 1988; Reuss et al., 1978). Little research has been done on the availability of Cd from fertilizers to cucumber. The few studies that determined uptake of Cd from biosolids by cucumber under greenhouse conditions showed the uptake was not influenced by pH (Falahi-Ardakani et al., 1988), but was affected by Cd concentrations in the growing medium (Moreno-Caselles et al., 2000; Obata and Umebayashi 1997; Tack et al., 1998). The applicability of these findings to fertilizer Cd is uncertain, especially under field conditions.

The objectives of this 2-year field study were to determine 1) the influence of liming on the accumulation in cucumber vine and fruit of Cd from a western phosphate rock (PR) or a TSP; 2) which index of soil Cd availability best predicts Cd concentrations in cucumber vine or fruit; and 3) the recovery of added Cd from the fertilizers in cucumber vine and fruit. A readily soluble Cd salt, $CdCl_2$, was included for comparison. The higher than normal application rates of the fertilizers used in this study helped determine the transfer efficiency and recovery in cucumber of Cd applied from the fertilizers.

Materials and Methods

This 2-year experiment was conducted on a Sultan silt loam at a Washington State University research farm near Puyallup, Wash. This soil is classified as fine-silty, mixed, mesic Aquandic Xerochrept. Treatments included three Cd sources (a western phosphate rock, a triple superphosphate, and $CdCl_2$), five application rates of Cd for each Cd source, and two lime rates. The total Cd concentrations were 40.9 $mg \cdot kg^{-1}$ for the PR and 125.1 $mg \cdot kg^{-1}$ for the TSP (Kuo et al., 2001). The Cd concentrations were determined by digesting 1g of each fertilizer in 20 mL of aqua regia overnight at room temperature, followed by analysis of Cd by flame atomic absorption spectrophotometry (AAS) with Deuterium arc background correction.

In Sept. 1998, part of the experimental site was limed with $CaCO_3$ at the rate of 4.4 Mg·ha^{-1}, which raised soil pH from 5.3 to ≈6.7. Lime was surface applied with a drop spreader and disked in. This was followed by applications of PR, TSP, and $CdCl_2$ with a drop spreader and incorporation into the soil using a rototiller to a depth of ≈12 cm. $CdCl_2$ was mixed with silica sand before application because of the small quantity of $CdCl_2$ used. The five application rates for the fertilizers were 0, 1×, 2×, 4×, and 8×, with the 1× rate being 645 kg·ha^{-1} for PR and 430 kg·ha^{-1} for TSP, which added Cd at 26.4 and 53.8 g·ha^{-1} for PR and TSP, respectively. The 1× rate of Cd for $CdCl_2$ was 90 g·ha^{-1}, the maximum allowable annual Cd input in Washington State (Washington State Department of Agriculture, 2000). The 1× rate for PR and TSP is the maximum allowable application rate of the fertilizers in a given year, as promulgated by the Washington State Dept. of Agr. Each treatment was replicated four times using a split-plot design. The size of each plot was 4.6 × 7.6 m, with a 3-m alley between plots. Cucumber was not planted until the following spring of each year. This allowed the added Cd from the fertilizers or $CdCl_2$ to equilibrate with the soil over winter.

The fertilizers and $CdCl_2$ were reapplied in Sept. 1999. This brought the cumulative application rates to 0, 2×, 4×, 8×, and 16× for the year 2000 study. The 1× rate for each fertilizer and $CdCl_2$ was the same as defined above.

The field was treated with glyphosate at 2.5 L·ha^{-1} in Spring 1999 and 2000, ≈2 months before planting. This was followed by uniform applications of 370 kg·ha^{-1} of KCl, 135 kg·ha^{-1} of KMAG (17.4% K, 10% Mg, and 21% S), and 22 kg·ha^{-1} of micronutrient mix (8% S, 1.5% B, 1.5% Cu, 3% Mg, and 6% Zn). The KMAG contained 0.78 mg·kg^{-1} Cd, and the micronutrient mix contained 10.5 mg·kg^{-1} Cd. The total input of Cd to the soil from the applications of these fertilizers (0.4 g·ha^{-1}) was very small, <1.5% of Cd added from PR or TSP at the lowest (1×) rate. The fertilizers were all incorporated into soil with a rototiller.

Cucumber (*Cucumis sativa* L.) 'Calypso' was planted in June 1999 and June 2000 with a row spacing of 81 cm and a seeding rate of 194,000 seeds/ha. A uniform band application of 22 kg·ha^{-1} N and 50 kg·ha^{-1} P as 11–52–0 (mono-ammonium phosphate), 5 cm away and 5 cm below the seed, was made at the time of seeding. A month after seeding, cucumbers were sidedressed with 80 kg·ha^{-1} N as NH_4NO_3. The concentration of Cd in the mono-ammonium phosphate fertilizer soluble in aqua regia was low, 1.51 mg·kg^{-1} Cd, and total Cd added from its application was <1.2% of the Cd added from the PR or TSP at the lowest (1×) rate.

For weed control during the growing season, the field was mechanically cultivated with a field cultivator until the plant canopy had developed to an extent that covered more than one-third of the space between two adjacent rows. Thereafter, the cultivation was done manually. Irrigation via sprinkler irrigation was applied periodically to maintain adequate soil moisture for plant growth.

Nine to ten weeks after planting, cucumber plants from 1.52 m of row in the center of each plot were cut just above soil surface. Fruit and vines were separated, and their fresh weights were determined. All plant tissues were washed twice with tap water and once with deionized water. Vines and cut fruit were air-dried first in a heated greenhouse (≈31 °C) for 48 h to reduce mass and volume before oven drying at 65 °C for 72 h for dry weight determination. The dry vine or fruit tissue was ground to <1 mm using a stainless steel grinder. For chemical analysis, 1.0 g of ground plant tissue was ashed in a muffle furnace at 500 °C (Chaney et al., 1982) for 12 h, followed by digestion in 10 mL of concentrated HNO_3 at 80 to 90 °C until dry. Residue was dissolved in 10 mL of 1.2 M HCl for Cd analysis by AAS with Deuterium arc background correction. The sensitivity for Cd determination was 0.025 mg·L^{-1}.

Soil samples were taken to a depth of 15 cm from the same area where the cucumber was harvested in each plot. Six cores were taken and mixed well. The soil was air-dried and crushed to pass a 2-mm sieve before chemical analysis.

Chemical analysis of the soil included pH (1 soil : 2 water), total Cd and the amount of Cd extractable by DTPA (diethylenetriaminepentaacetic acid) or 0.05 M $CaCl_2$, and the amount of P extractable by $NaHCO_3$. For total Cd determination, U.S. EPA method 3050 (USEPA, 1986) was used. Two grams of soil were digested in 20 mL of 1:1 HNO_3 and water in a beaker covered with a watch glass on a hot plate for 15 min without boiling. The solution was allowed to cool before being digested twice in 10 mL of concentrated HNO_3 for 30 min in each digestion. After the volume of the solution was evaporated down to 2 to 3 mL, it was digested on a hot plate again with 3 mL of H_2O_2 (30%) three or more times until the solution was clear. The solution was then digested with 2.5 mL of concentrated HCl for 15 min, filtered into a 25-mL volumetric flask through a 5-μm filter paper after it was cooled, and brought to volume with deionized water. The filtrate was analyzed for Cd by AAS.

The extractable Cd in the soil was determined by extracting the soil with 0.005 M DTPA (pH = 7.3) (1:2 soil to solution ratio, 2 h extraction time) or 0.05 M $CaCl_2$ (1:2 soil to solution ratio, 30 min extraction time). The suspension was centrifuged for 10 min at 1500 g_n, followed by filtration through a filter paper (pore size 5 μm) to remove any suspended organic debris, before being analyzed for Cd by AAS. The $NaHCO_3$-extractable P was determined by extracting the soil with 0.5 M $NaHCO_3$ (pH = 8.5) (1:20 soil to solution ratio, 30 min extraction time), followed by analysis of P by the method of Murphy and Riley (1962).

Quality control was performed using standard reference materials (National Institute of Standards and Technology [NIST], Gaitherberg, Md.). The analytical results were compared with the certified values for the standard reference materials. The reference materials included spinach leaves (NIST #1570) and San Joaquin soil (NIST #2709). The determined value for the spinach leaves was 2.69 ± 0.32 μg·g^{-1} Cd as compared to the certified values of 2.89 ± 0.07 μg·g^{-1} Cd. The determined value for the soil was 0.52 ± 0.01 mg·kg^{-1} Cd, which is slightly higher than the certified value of 0.38 ± 0.01 mg·kg^{-1} Cd.

Analysis of variance was performed using the GLM procedure in Statistical Analysis System (SAS Institute, 1989). Mean separations were performed using Duncan's Multiple Range Test. Linear regression analyses were performed for determining the relationship between soil total Cd and the amount of labile Cd extractable by DTPA or $CaCl_2$, and the relationship between concentrations of Cd in the harvested plant tissue and soil total Cd or labile Cd.

Results and Discussion

Cucumber vine and fruit yields. The vine dry matter yield (DMY) in each year significantly responded to increasing application rates of TSP, but not to increasing rates of PR (Table 1). The average vine DMY across lime rates increased from 1281 in the control to 1901 kg·ha^{-1} at the 8× rate in 1999 and from 2128 to 2777 kg·ha^{-1} at the 16× rate on a cumulative basis in 2000 for TSP (Table 1). The yield averaged across all fertilizer and $CdCl_2$

Table 1. Dry matter yields (DMY) of cucumber vine and fruit averaged across lime treatments as affected by application of different fertilizers varying in Cd concentration in 1999 and 2000.

1999				2000			
Fertilizer rate	Cd added ($g \cdot ha^{-1}$)	Vine DMY ($kg \cdot ha^{-1}$)	Fruit DMY ($kg \cdot ha^{-1}$)	Fertilizer rate	Cd added ($g \cdot ha^{-1}$)	Vine DMY ($kg \cdot ha^{-1}$)	Fruit DMY ($kg \cdot ha^{-1}$)
PR							
0×	0	1281 a[z]	1052 a	0×	0	2128 a	997 a
1×	25.8	1179 a	1097 a	2×	51.6	2090 a	1129 a
2×	51.6	1369 a	1018 a	4×	103.2	2152 a	1140 a
4×	103.2	1115 a	883 a	8×	206.4	2197 a	1007 a
8×	206.4	1222 a	1033 a	16×	412.8	1962 a	1252 a
Rate		NS	NS	Rate		NS	NS
Lime		NS	NS	Lime		**	NS
Rate × lime		NS	NS	Rate × lime		NS	NS
TSP							
0×	0	1281 c	1052 a	0×	0	2128 b	997 a
1×	53.8	1410 bc	1177 a	2×	107.5	2444 ab	1140 a
2×	107.5	1543 b	1159 a	4×	215.0	2441 ab	1258 a
4×	215.0	1531 b	1336 a	8×	430.0	2740 a	1173 a
8×	430.0	1901 a	1200 a	16×	860.0	2777 a	973 a
Rate		***	NS	Rate		**	NS
Lime		NS	*	Lime		*	NS
Rate × lime		NS	NS	Rate × lime		NS	NS
$CdCl_2$							
0×	0	1281 a	1052 a	0×	0	2128 a	997 a
1×	90	1066 b	886 a	2×	180.0	2079 a	1071 a
2×	180	1159 ab	884 a	4×	360.0	2005 a	1234 a
4×	360	1047 b	805 a	8×	720.0	1910 a	1058 a
8×	720	1182 ab	892 a	16×	1440.0	1961 a	1089 a
Rate		*	NS	Rate		NS	NS
Lime		NS	*	Lime		***	NS
Rate × lime		NS	NS	Rate × lime		NS	NS

[z]Values in same column for same testing treatment followed by a different letter are significantly different ($P < 0.05$), Duncan's new range test.
[NS,*,**,***]Nonsignificant or significant at $P = 0.05, 0.01, 0.001$, respectively.

treatments was higher in 2000 (2209 $kg \cdot ha^{-1}$) than in 1999 (1304 $kg \cdot ha^{-1}$), possibly due to the earlier planting date in 2000 (June 2) than in 1999 (June 14).

The significant correlation of vine DMY with $NaHCO_3$-P over the broad range of $NaHCO_3$-P test values in 1999 ($r = 0.74$, $P < 0.001$) or 2000 ($r = 0.63$, $P < 0.01$) reflected a relatively high P requirement for vine growth (Fig. 1). The amount of labile P extractable by $NaHCO_3$ increased P from 38.2 in the control to 127.5 $mg \cdot kg^{-1}$ at the 8× rate of TSP in 1999 for the unlimed soil. P was further raised to 147.1 $mg \cdot kg^{-1}$ at the 16× rate of TSP on a cumulative basis for the unlimed soil in 2000. In contrast, the 8× rate of PR in 1999 and the 16× rate on a cumulative basis in 2000 raised $NaHCO_3$-P levels only to 45.6 or 48.6 $mg \cdot kg^{-1}$, respectively. Inability of the added PR to increase vine DMY is not surprising, given the small increase in the $NaHCO_3$-P test values produced by the additions of PR. The PR is sparingly soluble even in moderately acidic soil (Armiger and Fried, 1957), unless acidulated before application (Iretskaya et al., 1998).

The $CdCl_2$ treatments had either a marginal or no effect on vine DMY, depending on the year (Table 1). No reduction in vine DMY occurred even with higher $CdCl_2$ additions in 2000. Cucumber vine DMY was not correlated with Cd additions in either year ($r^2 < 0.01$, $P > 0.05$). Liming did not consistently benefit vine DMY. Only in 2000 was the response to liming statistically significant at $P = 0.05$ (Table 1).

Unlike cucumber vine, cucumber fruit yield was unaffected ($P > 0.05$) by TSP regardless of the rate (Table 1). The increased vine growth with increasing TSP rates did not increase total fruit yield. Liming benefited fruit yield only for TSP and $CdCl_2$ treatments in 1999.

Concentrations of Cd in cucumber vine and fruit. Concentration of Cd in cucumber vine (vine Cd) ranged from 1.00 to 2.09 $mg \cdot kg^{-1}$, depending on the amount and source of Cd, and year (Figs. 2 and 3). Soil total Cd and vine or fruit Cd were significantly correlated irrespective of Cd source. Except for the marginal effect of liming on vine Cd for TSP treatments and on fruit Cd for PR treatments in 1999, liming generally had no effect on vine or fruit Cd for other Cd sources in 1999 or all Cd sources in 2000. Insensitivity of Cd accumulation by cucumber to pH was also found by Falahi-Ardakani et al. (1988) in a greenhouse study using biosolids as a Cd source. Lack of a pH influence on cucumber vine Cd and fruit Cd is in sharp contrast to what had been found for many other crops. The accumulation of Cd by vegetable, grain and other crops often is influenced by soil pH (Bell et al., 1991; Heckman et al., 1987; Mortvedt et al., 1981). Soil pH was anticipated to play an intimate role in controlling Cd availability to the plant, given its known ability to control Cd sorption by soils and the concentration or activity of Cd in soil solution (Eriksson, 1990; Kuo et al., 1985).

The slope of the response of vine or fruit Cd to increased soil total Cd did not vary significantly ($P > 0.05$) among the Cd sources (Table 2), despite a marked difference in the lability of

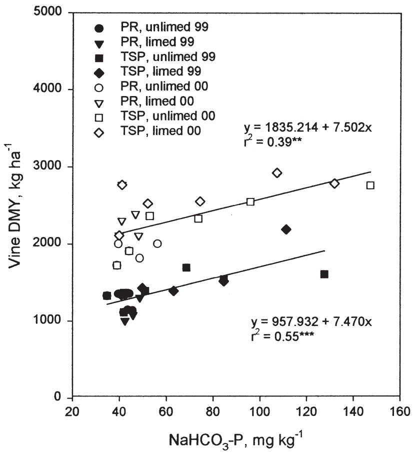


Fig 1. Relationship between soil labile P extracted by $NaHCO_3$ test and cucumber vine dry matter yield (DMY) in 1999 and 2000 in the limed and unlimed soil amended with phosphate rock (PR) or triple superphosphate (TSP).

their Cd that followed the following order: soluble Cd salt > TSP > PR (Kuo et al., 2001). It appears that as with pH, the lability of Cd in these Cd sources played no significant role in the accumulation of Cd by cucumber vine or fruit. This result raises the possibility that the solubility of Cd in soil solution was controlled predominately by cucumber exudates, rather than pH or Cd source. Plant exudates can modify the mobility of Cd or other elements in the soil rhizosphere and increase plant uptake of Cd (Krishnamurti et al., 1997; Mench and Martin, 1991). Further research is needed to clarify if cucumber plant roots regulate the solubility of Cd in soil solution.

The correlation of vine or fruit Cd with soil total Cd over all Cd sources at each lime rate was, in general, better than that with the labile Cd extractable by DTPA or $CaCl_2$ in 1999 (Fig. 4) or 2000 (Fig. 5). Across all Cd sources and lime rates, the correlation was best with soil total Cd, intermediate with DTPA-Cd and least with $CaCl_2$-Cd. This is a result opposite to what has been found for other crops including lettuce, maize, wheat, and spinach (*Spinacia oleracea* L.) (Kuo et al., 2001; Mortvedt et al., 1981; Smilde et al., 1992). Unlike soil total Cd, DTPA-Cd is moderately and $CaCl_2$-Cd highly sensitive to soil pH and Cd source (Kuo et al., 2001; Singh et al., 1995). For example, the concentration of $CaCl_2$-Cd for the soil treated with $CdCl_2$ at the rate of 16× in the year 2000 decreased from 0.266 ± 0.055 mg·kg⁻¹ Cd in the unlimed soil to 0.027 ± 0.003 mg·kg⁻¹ Cd in the limed soil. This compared with the reduction of DTPA-Cd from 0.580 ± 0.049 mg·kg⁻¹ Cd in the unlimed soil to 0.390 ± 0.066 mg·kg⁻¹ Cd in the limed soil. For plant Cd such as vine- or fruit-Cd that does not vary significantly with pH and Cd source, its concentration is better predicted by soil total Cd than by DTPA- or $CaCl_2$-Cd.

Cadmium uptake by cucumber vine and fruit. The total amount of Cd accumulated in the aboveground biomass, including vine and fruit, in the control treatment was very small, averaging 1.65 and 2.95 g ha⁻¹ across lime rates for 1999 and 2000, respectively. While it increased with increasing amounts of Cd added from the P fertilizers and $CdCl_2$ (Figs. 6 and 7), the total accumulated represented a very small fraction (<0.33 %) of the total Cd added. Increased Cd accumulation in the soil will occur if P fertilizer is applied at high rates that add more Cd than is removed by harvested cucumber biomass over a long period of time.

Of the total amount of Cd accumulated in the aboveground biomass in the control, most (78.6%) accumulated in the vine, which agrees with the finding of Falahi-Ardakani et al. (1988) that cucumber vine is the primary sink for Cd in the plant. The translocation of Cd from vine to fruit was limited.

The proportion of total Cd in the plant residing in the vine did not vary with rate of Cd addition or with Cd source. It was affected minimally by liming as well. Averaged over all Cd rates and sources, the proportion of total Cd in the plant residing in the vine was 77.5% in 1999 and 78.7% in 2000 for the unlimed soil as compared to 78.9% in 1999 and 82.7% in 2000 for the limed soil. Thus, the net amount of Cd removed from the soil is even lower than 0.1% of the Cd added if the cucumber vine is left in the soil as it often is. Under these circumstances, even more of the added Cd will accumulate in the soil.

Cadmium uptake coefficient (UC). The UC for Cd [UC(Cd)] of a metal describes the extent to which soil Cd is transferred from soil to plant. The UC for Cd essentially is the slope of the regression of vine- or fruit-Cd against soil total Cd (Figs. 2 and 3). The UC(Cd) for cucumber vine or fruit was unaffected (P > 0.05) by Cd source or lime rate (Table 2). Over all Cd sources and lime rates, the UC(Cd) averaged 1.92 in 1999 and 1.60 in 2000 for vine and 0.79 in 1999 and 0.72 in 2000 for fruit. The UC(Cd) for cucumber fruit is comparatively lower than that for such leafy vegetables as lettuce (ranging from 1.28 to 15.9) (Crews and Davies, 1985; Kuo et al., 2001; Smilde et al., 1992) and spinach (1.36 to 21.06) (Smilde et al., 1992) that are known to be high Cd accumulators. Cucumber is unique in that the typical effect of Cd source and pH on UC(Cd) for lettuce, spinach or other vegetable crops (Bell et al., 1991; Kiekens et al., 1984; Kuo et

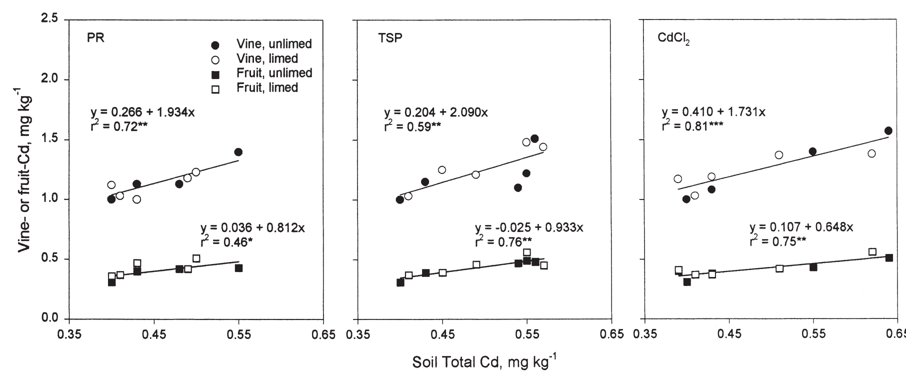


Fig 2. Concentrations of Cd in cucumber vine and fruit as affected by soil total Cd and liming in the soil amended with phosphate rock (PR), triple superphosphate (TSP), or $CdCl_2$ in 1999.

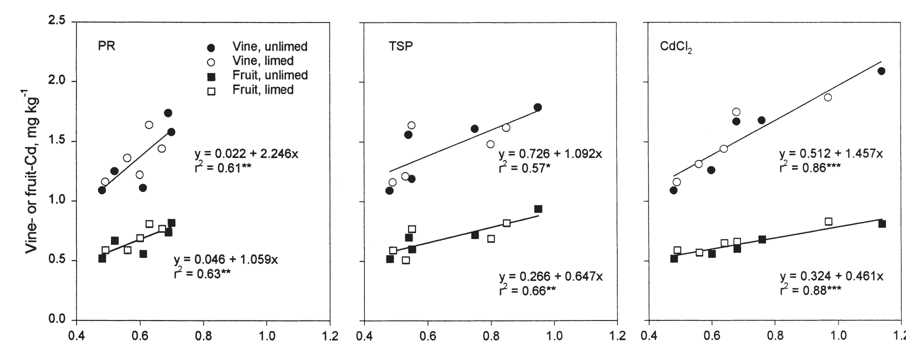


Fig 3. Concentrations of Cd in cucumber vine and fruit as affected by soil total Cd and liming in the soil amended with phosphate rock (PR), triple superphosphate (TSP), or $CdCl_2$ in 2000.

Table 2. Comparison of Cd uptake coefficient (UC)[z] for cucumber vine and fruit and soil Cd extractability in DTPA as affected by Cd sources

Cd source	Vine UC (Cd)	Fruit UC (Cd)	DTPA-Cd
1999			
PR	1.934	0.812	0.207
TSP	2.090	0.933	0.572
$CdCl_2$	1.731	0.648	0.754
	NS	NS	*
2000			
PR	2.246	1.059	0.232
TSP	1.092	0.647	0.402
$CdCl_2$	1.457	0.461	0.689
	NS	NS	**

[z]UC calculated based on soil total Cd

[NS,*,**]Nonsignificant or significant at $P = 0.05$ or 0.01, respectively.

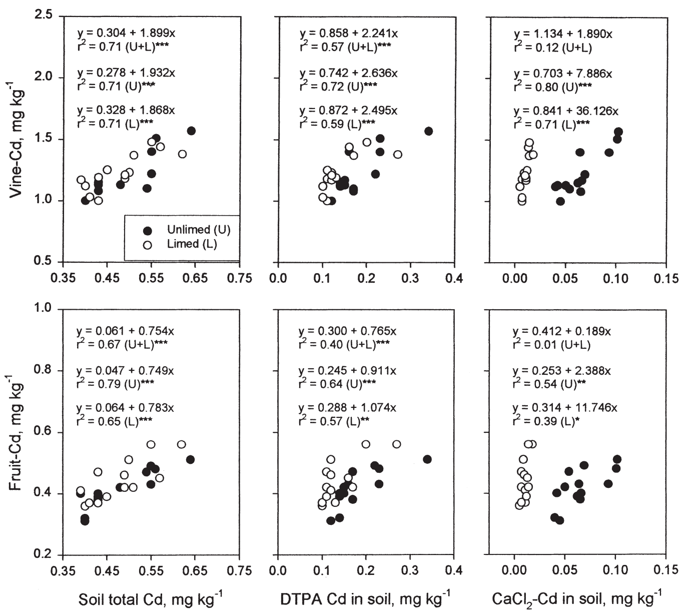


Fig 4. Relationship between concentration of Cd in cucumber vine or fruit and soil total Cd or labile Cd by DTPA or $CaCl_2$ extraction over all Cd sources for each or all lime rates in 1999.

al., 2001) was not similarly found for this plant. This is attributed to the lack of pH and Cd source effects on Cd accumulation by the plant, as mentioned earlier.

The UC(Cd) may also be measured based on the amount of labile Cd by DTPA or $CaCl_2$ extraction (Kuo et al., 2001; Smilde et al., 1992). Because there was a lower correlation of vine- or fruit-Cd with DTPA- or $CaCl_2$-Cd than with soil total Cd (Figs. 2 and 3), it was not advantageous to measure UC(Cd) based on the amount of labile Cd in the soil for cucumber. As the advantage has been demonstrated for lettuce (Kuo et al., 2001; Smilde et al., 1992), corn (Smilde et al., 1992) and ryegrass (Kiekens et al., 1984), it follows that crop species is a factor to be considered in deciding which index of soil Cd availability, total or labile Cd, should be used for measuring UC(Cd).

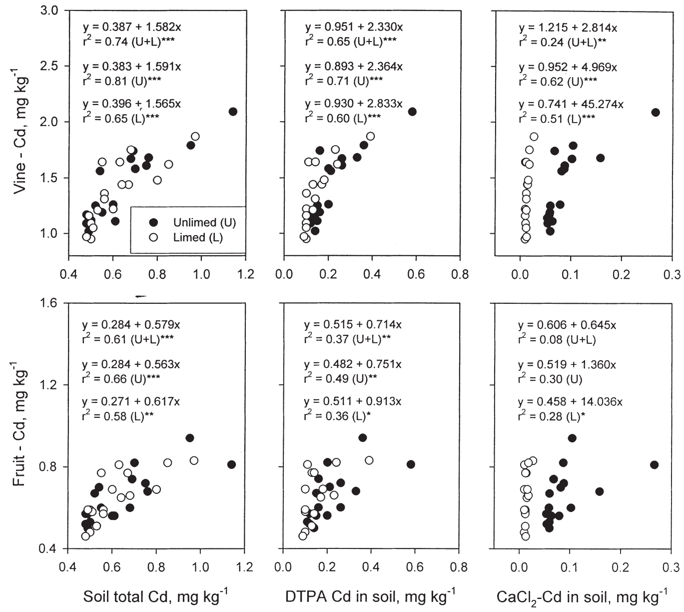


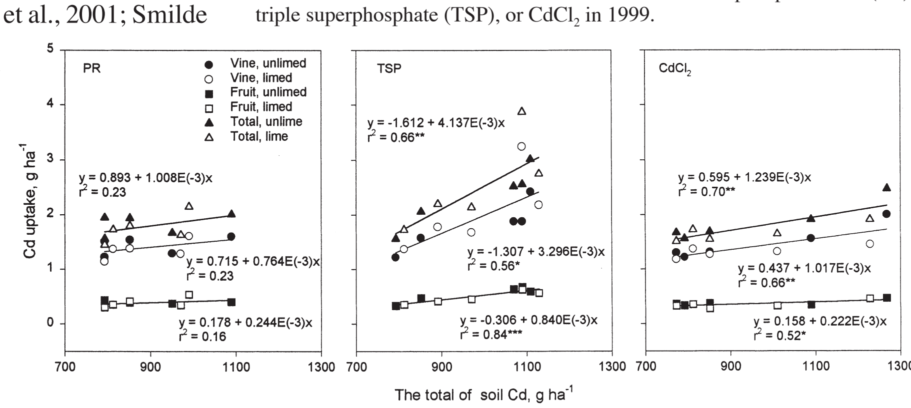
Fig 5. Relationship between concentration of Cd in cucumber vine or fruit and soil total Cd or labile Cd by DTPA or $CaCl_2$ extraction over all Cd sources for each or all lime rates in 2000.

Conclusions

Addition of the PR and TSP fertilizers at high rates increased soil total Cd, Cd extractable by DTPA or $CaCl_2$, and Cd accumulation by cucumber vine and fruit. However, only a very small fraction of Cd added was accumulated by the vines and fruit, and the majority of accumulated Cd resided in the vines. Increased soil accumulation of Cd over time should be expected from the applications of the fertilizers, particularly at high application rates and with vine residue returned to the soil.

Unlike leafy vegetable crops, cucumber vines and fruit accumulated Cd from the soil independent of pH or Cd source. This unique characteristic makes the Cd transfer efficiency better measured with soil total Cd than with the amount of labile Cd by DTPA for cucumber. It is unclear how the plant controlled the uptake of Cd and further research is needed to clarify this.

Fig 6. Uptake of Cd in cucumber vine or fruit or vine plus fruit as affected by the total amount of Cd in the surface soil amended with phosphate rock (PR), triple superphosphate (TSP), or $CdCl_2$ in 1999.



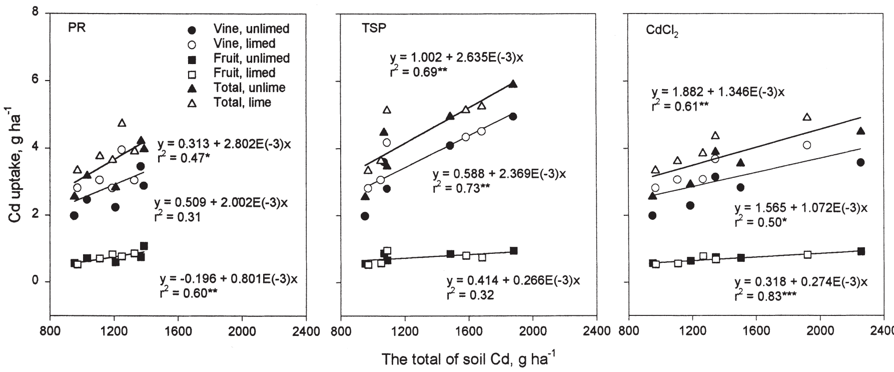


Fig 7. Uptake of Cd in cucumber vine, fruit, or vine plus fruit as affected by the total amount of Cd in the surface soil amended with phosphate rock (PR), triple superphosphate (TSP), or $CdCl_2$ in 2000.

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