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Effects of nickel and copper on *Acer rubrum*, *Cornus stolonifera*, *Lonicera tatarica*, a *Pinus resinosa*

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Red maple (*Acer rubrum*), yellow-stem dogwood (*Cornus stolonifera* 'Flaviramea'), and tartarian honeysuckle (*Lonic tatarica*) cuttings and red pine (*Pinus resinosa*) seedlings were grown in a controlled environment in aerated liquid culture wi or 10 mg·L^{-1} Ni^{2+} or 4 or 20 mg·L^{-1} Cu^{2+} singly or in combination (2 and 4 mg·L^{-1} or 10 and 20 mg·L^{-1}). Injury sympto included marginal and interveinal chlorosis, alteration of leaf pigmentation, severe leaf drop, and abnormally small leaves. W increasing metal levels, root tissues became severely discoloured, lateral roots were few in number, stunted, and thickened, bulbous root tips developed. Growth and development of plants were retarded in most metal treatments compared control plants. Tissue accumulation of metals generally increased with increasing Ni and Cu concentrations in the nut solutions, but tissue concentrations varied according to species, metal, and tissue analyzed. Pine needles did not accumul added Cu, while roots of all species contained very high concentrations of Cu. In the combination treatments, the presence elevated levels of Cu reduced Ni accumulation in the root tissues of all four species and pine stems and leaves and stems dogwood, compared with the single Ni treatments. In contrast, honeysuckle stems and pine needles had greater Ni accumulat from a combined Ni and Cu treatment than from the corresponding single treatment.

Introduction

The emission of large quantities of trace elements into the atmosphere, as a result of industrialization, has contributed significantly to environmental contamination. Primary base metal smelters are major sources of these emissions (Beavington 1975; Buchauer 1973; DeKoning 1974; Little and Martin 1972; Wood and Nash 1976). One of the world's principal ore deposits of nickel and copper is located in the Sudbury, Ontario basin. Mines and smelters in this region were established in the late 1800's and since that time large quantities of sulphur dioxide and metal particulates have been emitted. Emissions have contributed to the loss of vegetation on large areas close to the smelters and have resulted in metal contamination of soils and vegetation (Gorham and Gordon 1960; Hutchinson and Whitby 1974, 1977; Whitby *et al.* 1976).

In addition to metal contamination, several other factors, alone and in combination, may have interacted to reduce the amount of vegetation in the Sudbury area. Such contributing factors are lack of protected macroenvironments, soil acidity, extensive lumbering activities, severe forest fires, acute and chronic sulphur dioxide exposures (produced by the smelting and refining of sulfide ores), and susceptibility of plants, growing in a weakened condition, to insects and disease.

There is little documentation on the effects of injurious levels of trace elements on woody trees and shrubs even though they are important species in the reve tion of contaminated areas. Since Ni and Cu are predominant mineral elements and two of the ma components of particulate fallout in the Sudbury reg a solution culture study was established to determ visible toxicity symptoms, growth responses to th metals, and their accumulation in tissues of f temperate woody species that might be grown in region. Red maple (*Acer rubrum* L.), yellow-s dogwood (*Cornus stolonifera* Michx. 'Flaviramea tartarian honeysuckle (*Lonicera tatarica* L.), and pine (*Pinus resinosa* Ait.) were selected because are hardy in the Sudbury area, they represent genera are used to some extent in reclamation and revegeta in the area (especially *Acer* and *Pinus*), and cutti and seedlings were readily available.

Materials and methods

Partially rooted cuttings of yellow-stem dogwood tartarian honeysuckle were obtained from a commer nursery (John Connon Nurseries Ltd.) and cuttings of maple and 2-year-old seedlings of red pine were obtained f the Ontario Ministry of Natural Resources Tree Nursery a Williams, Ont. Cuttings and seedlings were exposed to 4 for approximately 60 days to ensure that bud dormancy broken. Roots were then thoroughly rinsed in distilled wa remove any adhering soil particles, and cuttings and seedl were rooted in deionized water-washed No. 16 (coarse) sand and grown for approximately 90 days. During this development period, plants were watered every 2nd day 250–300 mL of full strength Hoagland's nutrient solutio distilled water) maintained at a pH of approximately

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Every 7 days pots were thoroughly leached with distilled water.

Following the rooting period, plants were removed from the sand and placed in aerated full strength Hoagland's nutrient solution. Seven treatments were established using $NiSO_4$ as the Ni^{2+} source and $CuSO_4$ as the Cu^{2+} source: control (<0.1 mg·L^{-1} Cu^{2+} in the micronutrient portion of the nutrient solution), 2 mg·L^{-1} Ni^{2+}, 10 mg·L^{-1} Ni^{2+}, 4 mg·L^{-1} Cu^{2+}, 20 mg·L^{-1} Cu^{2+}, 2 mg·L^{-1} Ni^{2+} plus 4 mg·L^{-1} Cu^{2+}, and 10 mg·L^{-1} Ni^{2+} plus 20 mg·L^{-1} Cu^{2+}. Plastic pots (15 cm diameter) were lined with two (2-L size) plastic bags. Covers were made from black polyethylene taped to the sides of the pot, with a radial slit to allow plant placement and changing of solutions. Compressed air flowing through black plastic capillary tubes provided a continuous air flow into each solution. Solutions in the pots were topped up daily with their respective treatment solutions and changed once a week. At midweek, the pH value of the solution in each of the pots was determined and, if necessary, was adjusted with KOH to between 5.8 and 6.5.

There were three replicates in each treatment for each of the species. Pots were randomly placed in two controlled environment (model EY15) growth chambers. Day and night temperatures were 23.0 ± 1.1 and 18.0 ± 1.1°C, respectively. A 12-h photoperiod and thermoperiod were maintained for the duration of the experiment. A light intensity of approximately 21 klx (325 μE·m^{-2}·s^{-1} photosynthetically active radiation) was maintained at the top of the plant canopy, with an adjustable bank of lights which supplied 27% of the input voltage from incandescent bulbs and the remaining 73% from cool white fluorescent lamps. Relative humidity was approximately 75%. Air moved through the plant canopy at 15 cm·s^{-1}. These cultural conditions were in effect for the rooting of the plants and also during the treatment phase of the experiment. Plants were kept in the treatment solutions for 110 days.

Visual observations were recorded for each plant approximately every 5 weeks. Stem diameter was measured at the beginning and end of the experiment. At the end of the experiment total dry weights of plants were calculated from the weights of plant parts. Root systems were examined visually for colour, appearance of laterals and lateral primordia, and any unusual characteristics were noted.

Dry weights of plant parts were determined after drying in a forced air oven (65.0°C) for at least 48 h. Branches and roots were ground to pass through a 20-mesh screen and leaves and needles were ground to 40 mesh using a Wiley mill. A dry-ashing procedure was used to determine the Ni and Cu content of plant tissue (Heale 1980). Samples were analyzed using a Perkin-Elmer (model 5000) flame atomic absorption spectrophotometer.

Results

Visual symptoms

A general indication of Ni and Cu toxicity was the development of interveinal leaf chlorosis. The severity of chlorosis and the development of other symptoms, such as interveinal reddening, leaf tip blackening, abnormally small leaves, and leaf drop, were influenced by the trace element levels and combinations to which the individual species were exposed (Table 1). Root tissue developed necrosis and lateral roots were reduced in number, stunted, and thickened by the Ni and Cu treatments (Table 2). Lateral root primordia were few, enlarged, and necrotic. When higher levels of trace elements were added to the treatment solutions, greater distortions in root morphology and (or) orientation were evident.

Growth responses

Increases in stem diameter of maple and dogwood were severely retarded by 20 mg·L^{-1} Cu or the combination of 10 mg·L^{-1} Ni and 20 mg·L^{-1} Cu (Table 3). The other metal treatments did not retard stem diameter growth significantly. Treatment with Ni and (or) Cu did not significantly affect the average number, width, and length of maple leaves (Heale 1980). Total dry weight of maple plants (including leaves, stems, and roots) was highly variable and there were no significant effects of the Ni and Cu treatments. In dogwood the heaviest plants were in the 2 mg·L^{-1} Ni treatment rather than in the control treatment. Dry weight was markedly reduced by a solution Cu concentration of 20 mg·L^{-1} or its mixture with 10 mg·L^{-1} Ni.

Honeysuckle was much more sensitive to Ni and Cu than maple or dogwood. All metal treatments retarded or prevented stem enlargement and dry weight increase compared with control plants. Control honeysuckle plants also had the greatest number, width, and length of leaves (Heale 1980). In contrast, stem diameters were not significantly different among pine seedlings exposed to the Ni and Cu treatments. Needle elongation (measured on a primary lateral branch and on the terminal shoot) was retarded by the 20 mg·L^{-1} Cu treatment (Heale 1980). Pine dry weights were quite variable and no distinct pattern of metal effects could be identified.

Nickel accumulation

Nickel concentrations in leaves, stems, and roots of all species generally increased with increasing levels of Ni alone in the nutrient solutions (Table 4). The highest concentrations of Ni were found in roots, with stem concentrations intermediate. Nickel uptake was substantial for all tissues of 10 mg·L^{-1} Ni treated plants. The combination treatments revealed some interactions of the two trace elements. After treatment with either combination of Ni and Cu, roots of all four species did not contain as much Ni as roots from the corresponding single Ni treatments. The presence of 20 mg·L^{-1} Cu significantly decreased Ni accumulation by dogwood leaves, while either the 4 or 20 mg·L^{-1} Cu level in combination with Ni decreased Ni accumulation by stems. In contrast, honeysuckle plants treated with 10 mg·L^{-1} Ni and 20 mg·L^{-1} Cu in combination

TABLE 1. Visible symptoms of leaf injury on plants treated with Ni and Cu in complete nutrient solution

[Metal] in solution, $mg \cdot L^{-1}$					
Ni^{2+}	Cu^{2+}	Maple	Dogwood	Honeysuckle	Pine
2		L marginal and tip chlorosis	L interveinal chlorosis, some leaves	L–M marginal and interveinal chlorosis	M chlorotic needles
10		L–M interveinal chlorosis M interveinal and marginal purpling L leaf tip blackening	M–S interveinal chlorosis, new growth; new growth abnormally small L interveinal necrotic spotting	M–S interveinal chlorosis S leaf drop S inward rolling leaf tips and margins	M chlorotic needles M needle tip dieback of older needles
	4	M–S interveinal chlorosis L leaf tip blackening	S interveinal chlorosis, new growth	L marginal and interveinal chlorosis and purpling, no new growth	L chlorotic needles, older needles necrotic, wilted appearance of seedling
	20	M–S interveinal chlorosis	S leaf drop S interveinal chlorosis	M interveinal chlorosis S leaf drop	M chlorotic needles S needle tip dieback of older needles
2	4	M–S interveinal chlorosis L–M leaf tip blackening	M–S interveinal chlorosis L marginal and tip necrosis	L marginal and interveinal chlorosis L inward rolling leaf margins, no new growth	L chlorotic needles
10	20	ES interveinal chlorosis ES interveinal reddening	S interveinal chlorosis, leaves abnormally small	M interveinal chlorosis	M chlorotic needles M needle tip dieback of older needles

NOTE: L, slight; M, moderate; S, severe; ES, extremely severe.

TABLE 2. Visible symptoms of root injury on plants treated with Ni and Cu in complete nutrient solution

[Metal] in solution, $mg \cdot L^{-1}$					
Ni^{2+}	Cu^{2+}	Maple	Dogwood	Honeysuckle	Pine
2		orange–beige; thickened laterals	beige	orange–beige; few laterals, stunted	reddish brown
10		orange–beige; few laterals, stunted; enlarged tips; primordia originate close together (densely branched appearance)	beige; stunted laterals; slightly enlarged tips; numerous primordia at tips	orange; laterals with brown tips; numerous primordia of lateral tips (root wrinkled appearance)	reddish brown; stunted laterals, thickened
	4		brown; stunted laterals	orange–beige; few laterals, very stunted; very enlarged tips	reddish brown; few laterals
	20	brown; few laterals, thickened, stunted; very enlarged tips	dark brown; stunted laterals; primordia originate close together (branched appearance)	orange–brown; few laterals, stunted; dark brown tips	reddish brown; few, stunted laterals
2	4	orange–beige; numerous laterals, thickened; enlarged tips	light brown; stunted laterals; laterals originate close together (branched appearance)	orange–beige; few laterals, very stunted; very enlarged tips	light reddish brown; numerous laterals
10	20	brown; numerous laterals, stunted; primordia originate close together (densely branched appearance)	dark brown; stunted laterals	brown; few laterals, stunted; very enlarged, dark tips	reddish brown; numerous stunted, thickened laterals

TABLE 3. Stem diameter increase and dry weight of plants treated with Ni and Cu in complete nutrient solution

[Metal] in solution, mg·L^{-1}		Maple		Dogwood		Honeysuckle		Pine	
Ni^{2+}	Cu^{2+}	Stem diameter increase, cm	Dry weight, g·plant^{-1}	Stem diameter increase, cm	Dry weight, g·plant^{-1}	Stem diameter increase, cm	Dry weight, g·plant^{-1}	Stem diameter increase, cm	Dry weight, g·plant^{-1}
0		0.27*c**	4.33*a*	0.61*b*	48.56*bc*	0.37*b*	35.90*b*	0.01*a*	12.81*a*
2		0.16*abc*	3.56*a*	0.63*b*	74.64*c*	0.06*a*	12.42*a*	0.00*a*	9.56*a*
10		0.23*bc*	2.23*a*	0.18*ab*	14.34*ab*	0.01*a*	9.70*a*	0.00*a*	8.87*a*
	4	0.16*abc*	2.17*a*	0.13*ab*	15.82*ab*	0.01*a*	9.18*a*	0.03*a*	9.21*a*
	20	0.06*ab*	1.19*a*	0.02*a*	8.79*a*	0.00*a*	11.77*a*	0.12*a*	6.62*a*
2	4	0.19*abc*	2.04*a*	0.16*ab*	24.27*ab*	0.06*a*	5.28*a*	0.05*a*	10.10*a*
10	20	0.01*a*	1.22*a*	0.00*a*	8.47*a*	0.00*a*	7.26*a*	0.00*a*	12.07*a*

NOTE: Values are the means of three replicate plants.
**a, b, and c, mean separation within columns by Duncan's multiple range test at the 5% level.*

TABLE 4. Nickel accumulation (micrograms per gram dry weight) by leaves, stems, and roots of plants treated with Ni and Cu in complete nutrient solution

[Metal] in solution, mg·L^{-1}		Maple			Dogwood			Honeysuckle			Pine		
Ni^{2+}	Cu^{2+}	Leaf	Stem	Root	Leaf	Stem	Root	Leaf	Stem	Root	Needle	Stem	Root
0		5.4*a**	16.3*a*	7.7*a*	6.2*a*	6.1*a*	3.7*a*	4.8*a*	6.3*a*	24.4*a*	5.7*a*	3.4*a*	9.2*a*
2		15.4*a*	60.5*a*	111.2*b*	26.9*b*	30.4*b*	255.8*b*	18.5*ab*	28.5*a*	170.2*ab*	17.1*ab*	40.1*b*	358.3*b*
10		96.4*c*	231.9*b*	487.2*c*	81.7*c*	125.4*d*	602.5*c*	48.9*b*	157.5*b*	251.1*b*	14.3*ab*	122.0*c*	290.6*b*
	4	7.3*a*	19.9*a*	10.9*a*	12.5*b*	4.8*a*	3.1*a*	5.4*a*	11.9*a*	17.3*a*	9.4*ab*	4.7*a*	6.8*a*
	20	28.0*ab*	19.4*a*	29.5*a*	8.9*a*	6.4*a*	2.0*a*	7.4*a*	14.6*a*	6.8*a*	5.9*a*	3.7*a*	6.7*a*
2	4	20.6*ab*	50.6*a*	29.4*a*	25.4*b*	18.7*ab*	69.0*a*	25.5*ab*	41.9*a*	39.8*a*	21.8*bc*	32.2*b*	38.7*a*
10	20	60.1*bc*	186.5*b*	70.9*ab*	30.5*b*	52.9*c*	113.3*ab*	51.2*b*	312.1*c*	36.1*a*	28.4*c*	55.8*b*	71.5*a*

NOTE: Values are the means of three replicate plants.
**a, b, and c, mean separation within columns by Duncan's multiple range test at the 5% level.*

ed more Ni in stems than 10 mg·L^{-1} Ni treated Pine needles also contained more Ni after the mbination treatment than after the corresponding L^{-1} treatment. Pine stem response was opposite roots, both combinations markedly suppressed umulation compared with the single Ni treat-

accumulation

per concentrations generally increased in all in proportion to Cu in the nutrient solution but s were masked by high variability in maple and od leaves (Table 5). The highest Cu concentra- by far, were found in roots of all species, lly followed by stems. Copper concentrations in and roots of 4 and 20 mg·L^{-1} Cu treated maple neysuckle plants and roots of pine were substan- d did not differ from levels in the corresponding nation-treated plants. Copper concentrations in ots of high combination-treated dogwood were han those from the corresponding single Cu ent. This also occurred in pine stems. Root Cu in pine were very high regardless of the Cu ent. Copper levels in needles were unaffected by the nutrient solution.

Discussion

complex visible symptoms of Ni- and Cu-induced injury included chlorosis, pigmentation develop- and leaf abscission. Similar symptoms have been ed for Cd- and Zn-treated Norway spruce, white and red maple (Mitchell and Fretz 1977); Pb- d red maple and loblolly pine (Davis and Barnes ; Cu-treated azalea, boxwood, and cotoneaster s and Sydnor 1976); and red oak and white pine ed to Zn, Cd, Cu, and Pb (Jordan 1975). The Ni- induced root injury symptoms included stunt- kening, discoloration, disorientation, and sup- on of lateral root growth. Copper treatment of seedlings resulted in bulbous root tip development h and Specht 1952), as well as cessation of lateral xtension and bunching of secondary roots (Brams skell 1971; Smith and Specht 1952; Smith 1956). dy shrubs treated with Cu (Kuhns and Sydnor 1976) Pb- and Cd-treated American sycamore trees son *et al.* 1977) also had abnormal secondary root h. Crooke (1958) reported other Ni and Cu effects ots.

ntamination of nutrient solutions with elevated entrations of Ni and Cu significantly retarded stem th of maple, dogwood, and honeysuckle and dry ht accumulation of dogwood and honeysuckle in udy. Similarly, dry weights were reduced by toxic l levels in Cu-treated coffee (Aduayi 1972) and

TABLE 5. Copper accumulation (micrograms per gram dry weight) by leaves, stems, and roots of plants treated with Ni and Cu in complete nutrient solution

[Metal] in solution, mg·L^{-1}		Maple			Dogwood			Honeysuckle			Pine		
Ni^{2+}	Cu^{2+}	Leaf	Stem	Root	Leaf	Stem	Root	Leaf	Stem	Root	Needle	Stem	Root
0		45.8*a**	35.9*a*	73.7*a*	10.5*a*	13.9*a*	35.9*a*	34.4*a*	12.4*a*	24.4*a*	19.3*a*	7.9*a*	97.9*a*
2		46.2*a*	51.2*a*	110.4*a*	11.3*a*	9.2*a*	45.4*a*	75.3*ab*	15.8*a*	8.4*a*	11.5*a*	6.2*a*	140.7*a*
10		116.2*a*	25.7*a*	113.1*a*	13.1*a*	9.7*a*	46.3*a*	54.3*ab*	17.8*a*	8.9*a*	12.8*a*	8.2*a*	106.0*a*
	4	59.4*a*	250.7*bc*	1385.3*b*	28.7*a*	27.4*a*	2762.5*bc*	113.8*b*	62.4*a*	279.1*ab*	15.9*a*	49.4*ab*	3333.3*b*
	20	253.8*a*	409.9*c*	1517.7*b*	36.4*a*	85.4*b*	7666.7*d*	36.9*a*	360.3*b*	765.8*b*	14.3*a*	270.9*c*	4717.4*b*
2	4	37.9*a*	224.3*b*	1632.1*b*	37.7*a*	10.1*a*	2412.5*b*	36.0*a*	99.9*a*	343.8*ab*	17.3*a*	107.3*ab*	3531.8*b*
10	20	97.6*a*	316.9*bc*	1929.4*b*	31.9*a*	61.8*b*	3466.7*c*	36.2*a*	469.5*b*	813.3*b*	17.5*a*	152.8*b*	4395.8*b*

NOTE: Values are the means of three replicate plants.
*a, b, and c, mean separation within columns by Duncan's multiple range test at the 5% level.

Valencia orange seedlings (Smith 1956); Cd- and Pb-treated silver maple seedlings (Lamoreaux and Chaney 1977); and F- and Pb-treated loblolly pine and red maple (Davis and Barnes 1973).

Of the four species studied, honeysuckle was the most sensitive to all Ni and Cu concentrations in terms of growth retardation, while maple (stem diameter) and dogwood were highly sensitive to only the highest Cu concentrations. It was not possible to determine a growth effect in pine because of high variability and limited growth response. Significant differences among treatments in Ni accumulation were noted for all parts of all species, while high variability in Cu content of maple and dogwood leaves precluded identification of significant Cu-accumulation patterns. Copper content of pine needles was quite uniform regardless of treatment.

The observed general increases in tissue Ni or Cu concentrations with increasing solution Ni or Cu concentrations have also been noted for Cu accumulation in azalea, cotoneaster, and boxwood (Kuhns and Sydnor 1976); Cd and Zn concentrations in red maple, Norway spruce, and white pine (Mitchell and Fretz 1977); Cd and Pb in American sycamore (Carlson *et al.* 1977); and Cu, Zn, and Mn in citrus seedlings (Smith 1956).

The highest concentrations of Ni and Cu in all species were generally found in roots, with stem concentrations intermediate. Concentrations of Ni, Cu, and other trace elements were also greatest in root tissues of citrus seedlings (Smith and Specht 1952); European sycamore (Lepp and Eardley 1978); and white pine, red maple, and Norway spruce (Mitchell and Fretz 1977). Root concentrations were also quite variable in the present study. The location of these elements within root tissue was not identified. There was no desorption treatment prior to analysis so metal ions in the free space were included in the reported concentrations. However, there were some substantial differences among species in root metal content with greater differences for Cu than for Ni. Dogwood and pine had particularly high root Ni concentrations.

Copper inhibited Ni accumulation in certain cases. Either combination of Ni and Cu suppressed Ni accumulation by roots of all four species compared with the corresponding single Ni treatment. Dogwood leaf and stem and pine stem tissue accumulation of Ni was also suppressed in some combination treatments. Copper concentrations in dogwood roots, honeysuckle leaves, and pine stems were less with some combinations than with the corresponding single Cu treatment. Similarly, Cu and Zn were competitive inhibitors of Ni uptake in soybean (Cataldo *et al.* 1978). In contrast, honeysuckle stems and pine needles had higher Ni in some combination treatments than in the corresponding single Ni treatment. Similarly, Pb- and Cu-treated American sycamore seedlings had enhanced accumulation compared with single elements (Carlson *et al.* 1977).

The selections of the sulphate form and conc tions of Ni and Cu to be used were based on reported by others to reveal visual and (or) mo logical responses of various species to these ele (Whitby and Hutchinson 1974; Jordan 1975). Co trations that would result in rapid death of plants avoided. It is difficult to relate solution culture co trations directly to the available concentrations of n in contaminated soils. In such soils, the metal present in a number of chemical states with much being in the form of low molecular weight organic plexes. Solution culture experiments can only provi approximation of the quantity of available or ionic soluble form in the soil solution as maintaine exchange with other soil compartments. Such ex ments could be followed by soil experiments, prefe first in controlled environments and then outdo Comparison of symptoms and effects on plant solution culture with those in soil culture may a better estimates of available concentrations in the solution than those based on chemical extraction m ods.

The plant material used in these studies was obtained from the Sudbury area. It is recognized sampling of native woody plant material in the conta nated area as the source of cuttings and (or) seed have provided different patterns of response with tinctly less sensitivity to the metals. The use of sensit species may simulate more accurately the response species introduced for reclamation and revegetation, well as provide more complete visual and comparat expression of injury symptoms than would pla already growing in the contaminated area.

This study has provided base-line information injury symptom development and metal accumulati and distribution in four woody species exposed, un controlled environment conditions, to Ni and Cu aerated solution culture. Responses were characteri by high variability within and between species t masked treatment effects in many cases. Restric numbers of replicates in controlled environments a made it difficult to identify treatment effects. T information on symptoms, growth effects, and tiss concentrations can be utilized in experiments with so from contaminated areas. The distinct interactions of and Cu in affecting element uptake and distributi require further study since soils in regions like Sudbu will have a substantial content of both metals a competitive inhibition of uptake may be very importa Further research is also needed on the chemistry a physiology of trace element uptake from contamina soils in relation to the forms of these elements and th availability. Success in revegetation of trace elem contaminated areas, such as Sudbury, may be depend on understanding the actions and interactions of th elements in both the plant and the soil.