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Toxic Effects of Serpentine Soils on Plant Growth

Kim, Jeong-Myeong and Jae-Kuk Shim*

Department of Life Science, Chung-Ang University, Seoul 156-756, Korea

ABSTRACT: Serpentine soils are distributed in a small area in Korea, and generally exhibit high contents of Ni, Cr, Fe, Mn, Co and Mg. We investigated the growth of woody plants and herbs in the Andong serpentine area, Korea. *Pinus densiflora* and *P. rigida* growing on serpentine soils have high contents of Fe, Mg, Ni and Co, with contents approximately twice as high as those of non-serpentine plants. Tree species on serpentine soil also had lower ratios of tree height/DBH than trees in a control area. In greenhouse culture experiments on two bodenvag herb species, *Setaria viridis* and *Cymbopogon tortilis*, the biomass of the plants was significantly affected by soil type but not by seed origins. After 66 days, the growth of *S. viridis* and *C. tortilis* seedlings was significantly inhibited in serpentine soil, and the dry weight of each species showed significant negative correlations with soil heavy metal contents (Ni, Co and Cr). These results suggest that the growth of plants was inhibited by properties of the serpentine soil, and in particular, their high heavy metal concentration, which induced dwarfing in woody plants and reduction of total plant biomass in herbs.

Key words: Heavy metals, Plant growth, Serpentine soils, Ultramafic soils

INTRODUCTION

Serpentine soils are derived from igneous ultramafic rocks that have high concentrations of magnesium, iron and other metals such as nickel, chromium and cobalt. They are often lacking in major plant nutrients such as nitrogen, phosphorus and potassium, and biomass production depends on one or few limiting nutrients and heavy metal contents (Brooks 1987, Baker et al. 1992). Therefore the plant communities they support are distinctive. Serpentine vegetation in general appears more xeric, but not because of differences in moisture availability. Rather, limiting nutrient conditions reduce vegetation structure in ways that simulate the effects of drought. Serpentine vegetation shows lower productivity and biomass, and the plant species composition generally differs widely from that found on nearby non-serpentine soils. Many of the species occurring on both do so as different ecotypes (Proctor 1999, Brady et al. 2005).

A number of experiments have shown that the growth of plants of non-serpentine origin is usually inhibited on serpentine soils or in conditions simulating serpentine soils (Proctor 1971, Nyberg Berglund et al. 2003). In serpentine soils, nickel, while essential for plants at low concentrations, is toxic at higher concentrations.

In Korea, serpentine soils are restricted to Hongseong, Andong and Ulsan. The Andong serpentine area is conspicuous because of an exposed basset. Serpentine soil has high concentrations of Mg, Cr, Ni, and Mg/Ca, but a paucity of essential macronutrients such as K (Kim et al. 2006). Kim et al. (1997) have reported high absorption of Zn, Sc and Fe by *Gypsophila oldhamiana* at the Hongseong serpentine area, and Mun (1988) observed poor growth and low biomass of *Miscanthus sinensis* on serpentine gangue soils compared with that on non-serpentine soils.

Pinus densiflora and *P. rigida* are the most important tree species in the Andong serpentine area, where they present a xeric physiognomy compared with pine forests in a nearby non-serpentine area (Kim et al. 2006). The aim of this study was to compare the growth of *P. densiflora* and *P. rigida* in serpentine and non-serpentine areas, to determine whether the growth of plants is affected by seed origin or soil properties, and to evaluate the serpentine edaphic factors that affect the growth of each plant species.

MATERIALS AND METHODS

This study was conducted at the Andong serpentine area (E 128° 26'～128° 30', N 36° 31' ～ 36° 32') in 2005. There are no endemic plants in the area: *P. densiflora* and *P. rigida* communities and grass lands prevail at the site (Kim et al. 2006). Soil and plant samples were randomly collected from the Andong serpentine and nearby non-serpentine areas. Detailed physical and chemical properties of the soil and geographic characteristics of the site are presented by Kim et al. (2006).

We randomly placed twenty-two 5 × 5 m quadrats on the nor-

* Corresponding author; Phone: +82-2-820-5211, e-mail: shimjk@cau.ac.kr

thern and southern slopes of the serpentine area, and fourteen 5 × 5 m quadrats in a nearby non-serpentine area. We estimated the DBH and height of each *P. densiflora* and *P. rigida* individual (DBH > 2 cm) in the quadrats.

To determine the effects of serpentine soils on plant growth, we chose two plant species common to both serpentine and nearby non-serpentine areas: the annual plant *Setaria viridis* and the perennial plant *Cymbopogon tortilis* var. *goeringii*. In the culture experiments, we used seeds and soils collected from both the serpentine area and the non-serpentine area. We collected seeds of each species *in situ* and germinated and transplanted them at the two-four leaf stage in the next growing season. Growth conditions were maintained at 15～28℃ air temperature, 14 hours of daylight, and 90% soil water holding capacity. The seedlings were planted in plastic pots (diameter 16 cm, depth 18 cm) containing serpentine or non-serpentine soils. Ten replicates were planted for each species and soil type. At 14, 42, and 66 days after transplantation, plants were harvested, and the stem height was measured and the dry weight of the aerial part and root of each plant was gauged after drying at 80℃ for 48 hr. Chemical properties and heavy metal concentrations in soil and plant tissues are presented in Kim et al. (2006).

Data were analyzed with regression analysis and one-way ANOVA, and the statistical significance of the differences between treatment means were determined with the Turkey test ($p < 0.05$) in SPSS (ver. 12.0.1). We also determined correlation coefficients for the relationships between heavy metal contents and biomasses of plant tissue parts.

RESULTS AND DISCUSSION

Heavy Metal Contents of Pine Trees in the Serpentine Area

The heavy metal contents of *P. densiflora* and *P. rigida* tissues were approximately twice as high in plants collected from the serpentine site than in those collected from the non-serpentine site for each plant part (Table 1). Fe, Mg, Ni and Co contents of serpentine plants were higher than those of non-serpentine plants, but no differences in Cr concentration were found in *P. rigida*. On the other hand, the Ca content was higher in non-serpentine plant parts than in serpentine plant parts.

Growth of Pine Trees in the Serpentine Area

Tree heights of *P. densiflora* and *P. rigida* were shorter for plants of the same DBH in the serpentine area than in the non-serpentine area (Fig. 1). The pine trees with DBH≤5 cm in *P. rigida* communities are assumed to show higher height levels in serpentine area than in non-serpentine area, as a result of plantation. The most important factor affecting plant growth is probably the differences

Table 1. The element contents of plant tissues of two pine tree species growing in serpentine soil and non-serpentine soil in the Andong serpentine area in Korea. Values are the means of ten individuals

Elements (mg/kg)	*Pinus densiflora*				*Pinus rigida*			
	Serpentine		Non-serpentine		Serpentine		Non-serpentine	
	Leaf	Stem	Leaf	Stem	Leaf	Stem	Leaf	Stem
Fe	213.6	224.1	135.3	176.3	346.2	446.4	120.7	115.6
Mg	2457	2030	1288	719.5	4415	2091	1643	391.7
Ca	2395	2259.5	5890	3239.5	2863.5	1508	3552.5	2478
Ni	17.38	8.35	4.56	4.78	16.66	16.21	2.95	2.45
Cr	2.55	3.76	1.85	1.71	1.92	2.31	1.5	2.07
Co	0.57	0.54	0.23	0.29	0.47	0.76	0.33	0.26

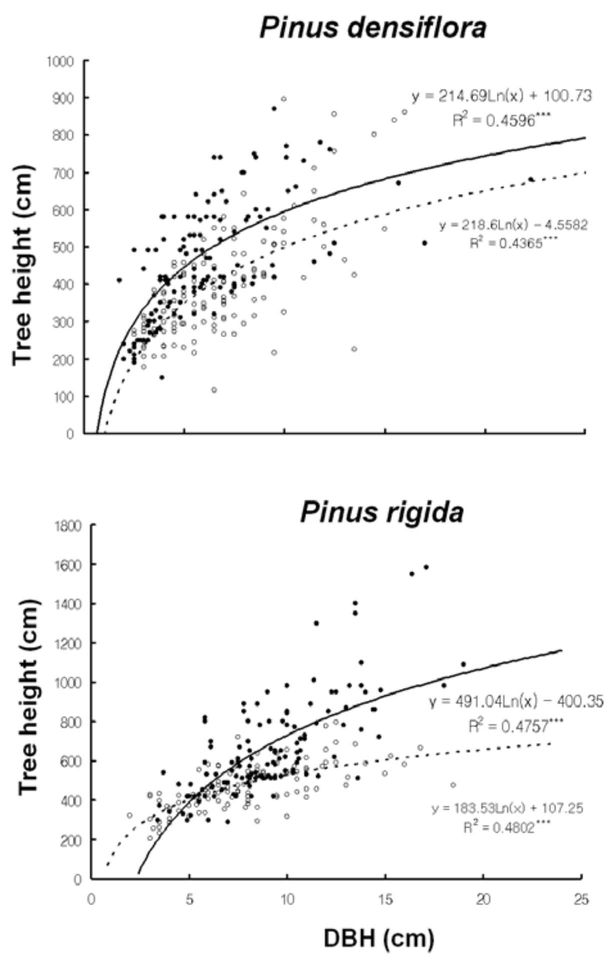

Fig. 1. DBH-Height curves of *Pinus densiflora* and *Pinus rigida* in the Andong serpentine area. -●-; non-serpentine area, --○--; serpentine area ($^{***}P < 0.001$).

in metal concentrations between the two soil types, with the serpentine soil having greater concentrations of Mg, Cr, Cu, Co, and Ni.

Heavy metals in soil can affect plant growth directly or indirectly (Yang 1990). Seo et al. (2006) reported that germination rates of *P. densiflora* in culture experiments using mine soils with high As, Zn, Cd, Pb and Cu were higher than those of other woody plants, but that they decreased with increased As concentrations. *P. densiflora* showed the highest germination rate among the plants tested, although germination in mine tailings was still lower than that in normal soils (Lee and Cho 2000). The growth of *P. densiflora* was inhibited on soil mixed with mine tailings rich in heavy metals, but the growth on mine tailings was improved by fertilizer treatment (Lee and Cho 2000, Seo et al. 2006).

In this study, the growth of *P. densiflora* from non-serpentine areas was higher than that in serpentine areas, but the difference was not large compared to the difference for *P. rigida*. *P. rigida* communities in the serpentine area were created by plantation, so the difference in plant height might increase with increasing DBH because of adaption.

Growth Responses of Two erbs to Serpentine Soil

The growth rates of *S. viridis* and *C. tortilis* in the culture experiment did not differ for seeds collected from serpentine and non-serpentine sampling sites, but did differ for plants cultured on serpentine and non-serpentine soils (Fig. 2). After 66 days of cultivation, the stem heights of *S. viridis* and *C. tortilis* cultured on non-serpentine soils were two times higher than those of plants cultivated on serpentine soils, while the stem heights did not show significant differences among plants from seeds of different origin grown on each type of soil.

The dry mass of aboveground parts and roots of *S. viridis* and *C. tortilis* showed a similar pattern of variation across different soil conditions (Fig. 3). Reduced plant growth on serpentine soils despite high P and organic matter contents seems to be due to the effects of higher heavy metal contents. Heavy metals can cause metabolic disorders and growth inhibition for most plants species at high doses (Fernandes and Henriques 1991, Claire et al. 1991). Cu and Cr have been reported to significantly decrease plant water potential Chatterjee and Chatterjee (2000), and Cu and Ni cause a 58～70% reduction in shoot elongation in alfalfa plants at a dose of 40 ppm (Peralta et al. 2000).

Huillier and Edighoffer (1996), Wong and Bradshaw (1981) reported significant effects of a number of metals on shoot growth. The effects on shoot growth may be secondary results of the effects of toxins on root functions such as water and nutrient uptake.

The dry masses of plant tissues were closely correlated with the heavy metal contents such as Co, Cr and Ni. Among the metals, levels of Ni and Co in plant tissues differed most dramatically between plants growing on serpentine and non-serpentine soils (Huillier and Edighoffer 1996, Tilstone and Macnair 1997). Root growth of both plant species (measured as change in mass) showed a stronger correlation with heavy metal concentrations than growth of the aerial parts (Table 2 and 3). Although this result is not consistent with the results of Wong and Bradshaw (1981), it suggests that the effects of heavy metals on the growth of roots might be more dramatic than those on other parts of plants.

This study showed that Ni and Co had more negative impacts on a growth of plants than Cr. Rout et al. (2000) observed that seeds collected from metal-contaminated sites showed higher germination and growth rates in plots containing metals than seeds from a

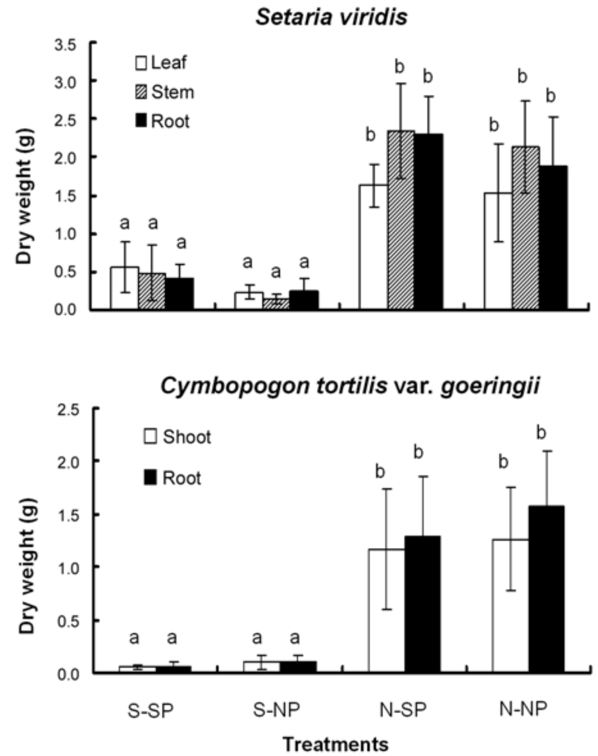

Fig. 2. Stem heights of *S. viridis* and *C. tortilis* in culture experiments. The seeds and soil were collected in serpentine and non-serpentine area. The culture experiments were performed in a cross manner according to the origins of the seed and soil samples. Bars indicates standard deviations and values followed by different letters mean significant differences for each harvest interval according to one-way ANOVA ($n = 10$, $P < 0.05$). S-SP; serpentine plant on serpentine soil, S-NP; nonserpentine plant on serpentine soil, N-SP; serpentine plant on serpentine soil, N-NP; nonserpentine plant on nonserpentine soil.

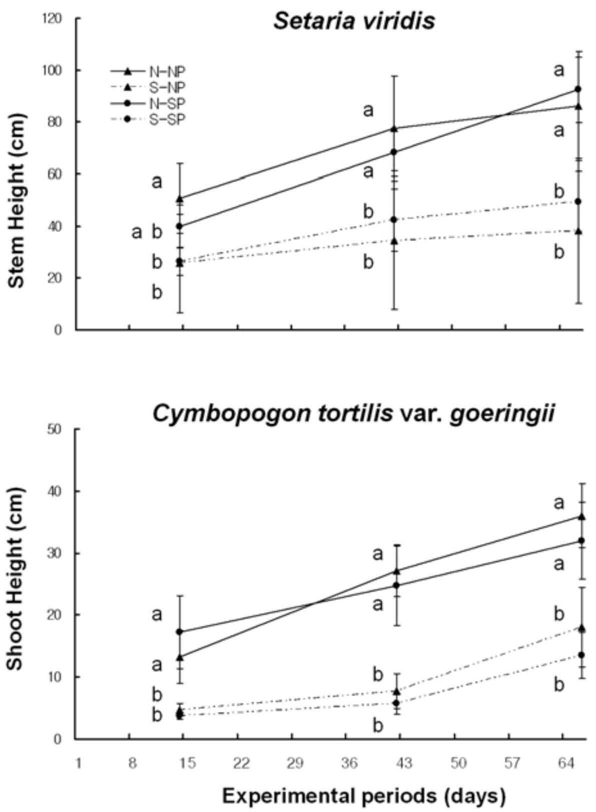

Fig. 3. Dry mass of plant parts for *S. viridis* and *C. tortilis* in culture experiments. Bars indicate standard deviations and different letters indicate statistical differences among plant tissues in the treatment according to the one-way ANOVA ($n = 10$, $P < 0.05$). S-SP; serpentine plant on serpentine soil, S-NP; nonserpentine plant on serpentine soil, N-SP; serpentine plant on serpentine soil, N-NP; nonserpentine plant on nonserpentine soil.

control site, suggesting the development of metal tolerance among plants in metal-rich soils. However, we did not find increased metal tolerance in seeds originating in serpentine soils. Nagy and Proctor (1997) reported that low nutrients, rather than toxic metals, caused the low plant cover observed in serpentine soils. However, in the Andong serpentine area, the nutrient contents in the soil did not differ substantially between serpentine and non-serpentine areas, but there were large differences in the contents of heavy metals such Ni, Cu, and Co. Therefore, metal contamination of soil seemed to be the primary cause of the negative effects of serpentine soils on the growth of the experiment species.

In this study, there were significant differences in the growth of pine trees and herbaceous species between serpentine and non-serpentine sites that were probably due to the presence of heavy metals in soil, regardless of seed collection site. It is apparent that plants growing in serpentine areas possess an integrated complex of

Table 2. The heavy metal concentration of *S. viridis* and *C. toritilis* tissues in culture experiments. See Fig. 2 for abbreviations

Plant and soil combination	Parts	Ni (mg/kg)	Cr (mg/kg)	Co (mg/kg)
Setaria viridis				
N-NP	Leaf	8.1	11.6	0.5
	Stem	2.0	2.0	0.2
	Root	18.4	22.3	0.1
S-NP	Leaf	31.4	14.6	2.6
	Stem	23.2	5.1	1.5
	Root	301.7	84.7	24.2
N-SP	Leaf	8.2	12.1	1.0
	Stem	5.2	4.7	0.5
	Root	22.8	27.5	0.5
S-SP	Leaf	26.4	13.4	1.4
	Stem	13.2	3.5	1.1
	Root	288.0	83.0	23.4
Cymbopogon tortilis var. *goeringii*				
N-NP	Shoot	0.7	2.3	0.1
	Root	0.1	34.4	0.3
S-NP	Shoot	31.9	11.4	3.0
	Root	303.9	118.2	34.1
N-SP	Shoot	16.0	4.5	0.2
	Root	22.0	34.6	0.4
S-SP	Shoot	25.9	5.6	1.7
	Root	202.2	94.8	29.5

Table 3. Correlation coefficients (*Pearson's coefficients, R*) between dry mass production and heavy metal contents for each plant part.

		Ni	Cr	Co
S. viridis	Leaf	−0.926	−0.382	-0.956^{*}
	Stem	-0.998^{**}	-0.963^{*}	−0.877
	Root	-0.984^{*}	-0.974^{*}	-0.983^{*}
C. tortilis	Shoot	−0.889	−0.754	−0.917
	Root	−0.949	-0.959^{*}	-0.982^{*}

n = 4; Individual measurements were means of 10 replicates.
$^{*}p < 0.05$
$^{**}p < 0.01$

adaptations to cope with a range of environmental stresses through means of metal tolerance such as metal exclusion (Baker et al. 1986, Baker 1987).

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