

## CCA 처리 목재로 지은 세 개의 통나무 구조물과 방음벽 주변 토양에서 크롬, 구리 및 비소의 공간적 분포

김희갑\* · 송병열 · 구진희

강원대학교 환경과학과

## Spatial Distributions of Chromium, Copper, and Arsenic Concentrations in Soils Near Three Log Structures and a Sound Barrier, All Constructed with CCA-treated Wood

Hekap Kim\* · Byeongyeol Song · Jinhoi Koo

Department of Environmental Science, Kangwon National University

### ABSTRACT

This study was conducted to investigate the spatial distributions of chromated copper arsenate (CCA) metals in soils around three log structures and a sound barrier, all built with CCA-treated wood. Sixty-six surface and 35 profile soil samples were collected around the wood structures in addition to 13 background soil samples. The concentrations of chromium, copper, and arsenic in the soil samples collected in the vicinity of the structures were higher than those in the background samples, except in the case of one structure. The concentrations in the surface soils adjacent to the 3-year-old structures seemed to be higher than those in the soils adjacent to the 8-year-old ones. Although the lateral distributions of the metals varied with the structures, chromium and arsenic appeared to show concentration gradients within 20-60 cm and 40-100 cm, respectively. Copper seemed to be the least mobile, displaying concentration gradients only within 20 cm. Even though there were no explicit vertical concentration gradients for any of the metals according to the profile soil sample analysis, chromium and copper seemed to show concentration gradients only up to 5 and 10 cm, respectively, whereas arsenic showed gradients up to 35 cm. At study sites, it was evident that heavy metals leached into soil from CCA-treated wood were confined to neighboring areas both laterally and vertically, and that any plausible ecological impact may occur only within a small range.

**Key words :** CCA, Log structure, Metals, Sound barrier, Spatial distribution

### 요 약 문

본 연구는 chromated copper arsenate(CCA)로 처리된 목재로 지은 세 개의 통나무 구조물과 하나의 방음벽 주변 토양에서 CCA 금속들의 공간적인 분포를 조사하기 위해 수행되었다. 13개의 배경 토양 시료뿐만 아니라 목재 구조물 주변에서 66개의 지표 및 35개의 종단면 토양 시료를 채취하였다. 구조물에 인접한 곳에서 채취한 토양 시료에서 크롬, 구리 및 비소의 농도는 하나의 구조물을 제외하고는 모두 배경 토양에서의 농도보다 높았으며, 3년 된 구조물에 인접한 표토에서의 농도는 8년 된 구조물에서의 농도보다 높게 나타났다. 비록 금속들의 수평 분포는 구조물에 따라 다르긴 하였지만, 크롬과 비소는 각각 20-60 cm 및 40-100 cm 내에서 농도 구배를 보이는 것 같았다. 구리는 가장 이동성이 작아서, 단지 20 cm 이내에서만 농도 구배를 나타냈다. 종단면 토양 시료 분석에 따르면 어떤 금속도 명확한 수직 분포를 보이지는 않았지만, 크롬과 구리는 각각 5 및 10 cm까지, 그리고 비소는 35 cm까지 구배를 보였다. 이 연구의 대상지역에서 CCA로 처리된 목재로부터 토양으로 용탈된 금속들은 수평 및 수직으로 인근 지역에 한정적으로 이동하여 분포하고, 가능한 생태적인 영향은 작은 범위 내에서만 일어날 것임을 보여주었다.

**주제어 :** CCA, 통나무 구조물, 금속, 방음벽, 공간적 분포

\*Corresponding author : kimh@kangwon.ac.kr

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## 1. Introduction

Chromated copper arsenate (CCA)-treated wood has been extensively used for outdoor applications such as decks, picnic tables, fences, walkways, playground equipment, sound barriers, and log structures in Korea since the 1980s. However, many studies have reported that chromium, copper, and arsenic leach from outdoor structures built with CCA-treated wood, resulting in the contamination of neighboring soil environments (Stilwell et al., 1997; Hingston et al., 2001; Stilwell and Graetz, 2001; Chirenje et al., 2003; Townsend et al., 2003; Zagury et al., 2003; Lebow et al., 2004; Gezer et al., 2005; Lebow and Foster, 2005; Kim et al., 2006; Robinson et al., 2006). Therefore, concern has arisen regarding possible human and ecological health impacts, leading to the ban (in Denmark, Poland, Switzerland, Indonesia, etc.) or limited use (in Finland, Sweden, Greece, Canada, USA, etc.) of CCA-treated wood. In like manner, Korea's Ministry of Environment (MOE) has banned the distribution of CCA-treated wood in Korea as of August 1, 2007, primarily based on the findings of the authors' research group (Kim et al., 2006; Kim et al., 2007).

In laboratory leaching tests, either arsenic or copper has been reported to be the most leachable component (Cooper, 1991; Breslin and Adler-Ivanbrook, 1998; Lebow et al., 1999; Townsend et al., 2001; Townsend et al., 2003). Leached metals in soil subsequently migrate to neighboring environments. Arsenic usually migrates longer distances than the other two metals, but the concentration gradients of the three metals appear to be limited within 100 cm both laterally and vertically (Bhattacharya et al., 2002; Chirenje et al., 2003; Zagury et al., 2003; Gezer et al., 2005; Lebow and Foster, 2005; Kim et al., 2007).

However, most of the above studies employed relatively large spatial sampling intervals (e.g., 0, 50, and 100 cm), except one study (Townsend et al., 2003), which employed approximately 2.5 cm intervals in profile sampling. Therefore, detailed studies on lateral and vertical gradients of metal concentrations

are limited. Moreover, metal distribution patterns in soil varied greatly among the studies. These variations can be attributed to age differences among the wood structures, varying extents of metal leaching into soil, ground surface inclination, soil surface conditions (e.g., lawn), soil compactness, and other soil physicochemical properties (e.g., pH, particle size distribution, electrical conductivity, cation exchange capacity, organic-matter content) (Tyler and McBride, 1982; Masscheleyn et al., 1991; Kartal et al., 2007; Kim et al., 2007).

Even though CCA-treated wood will, after August 1, 2007, no longer be used in constructing new structures in Korea, CCA metals can continue to leach from existing structures, since the new regulation does not require that those structures be removed. Therefore, continuous monitoring is necessary to investigate the possible impact of CCA-treated wood structures on humans and ecosystems. The present study was undertaken for the purpose of extensively investigating lateral and vertical distributions of chromium, copper, and arsenic around four CCA-treated wood structures (three log structures and a sound barrier).

## 2. Materials and Methods

### 2.1. On-site identification of CCA-treated wood

On-site identification of CCA-treated wood for each structure was conducted using Chrome Azurol solution (Blassino et al., 2002). The solution was sprayed onto the wood surface, which turned deep blue within a minute due to the formation of a complex between copper and Chrome Azurol. All of the structures were found to contain copper, suggesting that all were built with CCA-treated wood (CCA is the only copper-containing wood preservative used in Korea since the 1980s).

### 2.2. Soil sampling

The three log structures, located in a mountainous area of Chuncheon, Korea, included a water supply facility (A), a cabin (B), and a lecture hall (C). Structures A and B were 8 years old, whereas

structure C was 3 years old. The soil surface around structure A was covered with gravel and the soil was relatively hard. The soil around structure B was less compact than that around structure A. No vegetation was found on the soil surface around structures A and B. The soil around structure C was covered with grass. The wood used in all three structures was Western hemlock, and the surfaces of structures B and C were coated with an oil stain. Some parts of the wood surfaces displayed a green color due to the leaching of oxidized copper. In order to investigate the lateral distribution of the three metals for each structure, surface soil samples (composite samples 0-2.5 cm in depth) were collected in polyethylene zipper bags at five distances (0, 25, 50, 75, and 100 cm) for each structure. A total of 45 samples (15 from each structure) were taken. In addition, duplicate composite background samples were collected for each structure at locations at least 5 m from the structure. Profile soil samples were collected using a core sampler at locations 10 cm from structures B and C in order to examine the vertical distribution of the three metals. For structure B, seven samples were collected to a depth of 35 cm, at 5 cm intervals. For structure C, samples were collected at two locations to the depths of 80 (C-1) and 60 (C-2) cm, respectively. Table 1 summarizes each structure and the number of samples obtained.

A sound barrier (structure D) was built along one side of a four-lane motor road over approximately 0.5 km. It was composed of 2 m-stacked CCA-treated wooden planks on the top of a 1 m-high concrete base. The road side (approximately 30 cm wide) of the sound barrier was covered with grass and on the

other side was a ridge of approximately 15 degree inclination, from which soil samples were collected. Eighteen composite surface soil samples were collected at three locations, to a distance of 100 cm from the structure, at 20 cm intervals. Three additional samples were taken at locations adjacent to the structure. A total of 21 surface soil samples were obtained. Profile soil samples were obtained using a core sampler at two locations approximately 3 cm from the sound barrier at depths of 5, 10, 15, 20, 25, 30, and 35 cm. Seven background composite surface soil samples were collected at locations at least 6 m from the structure (Table 1).

### 2.3. Measurement of soil physicochemical properties

The collected soil samples were air-dried at ambient temperature for 2 days, then sieved over a 2 mm mesh. The larger materials were discarded and the remainder was ground using a ceramic mortar and a pestle. Twenty-seven log and 12 sound barrier soil samples were analyzed for pH, electrical conductivity (EC), organic-matter content (OM, %), and grain size distribution.

The soil pH was measured at room temperature using a pH meter (Accumet AP 62, Fischer Scientific) after 10 g of the sieved soil was thoroughly mixed with 10 mL of deionized water for 30 min (Jones, 2001). The EC was measured following the 1:1 water/soil extraction method, whereby 20 cm<sup>3</sup> of soil and 20 mL of deionized water were thoroughly stirred in a 50 mL beaker for 15 min (Jones, 2001). The soil OM (%) was measured following the method described by Ben-Dor and Banin (1989). A soil sample (5.0 to 10.0 g) was dried at 105°C for 4 hr

**Table 1.** Description of CCA-treated wood structures, and the number of soil samples collected

Structure	Type	Age (years)	Number of soil samples collected		
			Surface soil	Profile soil	Background soil
A	Water supply	8	15	0	2
B	Log cabin	8	15	7	2
C	Lecture hall	3	15	14	2
D	Sound barrier	3	21	14	7
Total (114)			66	35	13

and then heated at 400°C, and the percent OM in the soil sample was calculated by dividing the loss in weight between the two temperatures by the weight at 105°C. The grain size distribution was measured according to the Bouyoucos hydrometer method (Bouyoucos, 1936).

#### 2.4. Analysis of soil samples for metals

Extraction of the metals from the dried soil samples was performed following the U.S. EPA Method 3051A (U.S. EPA, 1998), with some modifications. One gram of each soil sample was digested using concentrated (60%) nitric acid in a microwave oven (EnviroPrep Q 45, Questron Technologies, Co.) at 150°C for 20 minutes (30% for 10 min and 70% for 10 min). The extract was filtered through a Whatman No. 2 paper filter (pore size: 8 µm) and then through a Whatman hydrophilic PVDF syringe filter (pore size: 0.2 µm). The filtrate was diluted to 100 mL in a volumetric flask using deionized water.

The prepared samples were analyzed for total chromium, copper, and arsenic contents using an atomic absorption spectrometer (SpectraAA-400, Varian). Chromium and copper were analyzed by the graphite furnace-AAS method (GTA-96, Varian). Arsenic was analyzed by the hydride-AAS method using a vapor generation accessory (VGA-76, Varian), following the treatment of the samples with L(+)-ascorbic acid and KI to convert As (V) to As (III) (Fleming and Ide, 1976).

Blank samples were analyzed prior to the sample analysis, and duplicate samples were run every 10 samples. A calibration standard was analyzed every 10 samples for each metal. The method reproducibility (as the relative percent difference, RPD) of the duplicated samples for each metal ranged from 1.3 to

3.1%. The soil matrix spike recovery percents for chromium, copper, and arsenic ranged from 94.4 to 103%. The method detection limits (MDLs) for chromium, copper, and arsenic were estimated to be 0.10, 0.30, and 0.095 mg/kg, respectively.

### 3. Results and Discussion

#### 3.1. Soil physicochemical properties

Table 2 shows the physicochemical properties of the selected soil samples. The average soil pH values at structures A and D were within the neutral range (7.3 and 6.5, respectively), whereas those at structures B and C were slightly acidic (5.6). The average EC values at the three log structures (A, B, and C) ranged from 13.9 to 42.7 µS/cm, whereas that at the sound barrier structure D was higher than that at the log structures, amounting to 86.8 µS/cm. The average OM contents (%) at all three structures were low (<1%), ranging between 0.29 and 0.85%. The average grain size distribution showed that the soil at structure D contained the highest amount of clay (31.9%) and that the soil at structure C contained the lowest (1.7%). Structures A and B showed similar grain size distributions.

#### 3.2. Comparison of metal concentrations in soils adjacent to structures

The chromium, copper, and arsenic concentrations in the surface soils adjacent (within 5 cm of the structures) to the structures were compared with those in the background surface soil samples. Nine samples for structures A, B, and C (3 samples for each) and 6 samples for structure D were selected for this comparison (Table 3).

**Table 2.** Physicochemical properties of selected soil samples

Structure	pH	EC (mS/cm)	OM (%)	Grain size distribution (%)		
				Sand	Silt	Clay
A	7.3 ± 0.5	42.7 ± 20.9	0.43 ± 0.09	62.8 ± 4.2	23.4 ± 1.3	13.8 ± 3.5
B	5.6 ± 0.5	20.4 ± 5.0	0.85 ± 0.13	60.7 ± 12.8	21.2 ± 4.6	18.1 ± 9.4
C	5.6 ± 0.1	13.9 ± 3.8	0.29 ± 0.07	85.2 ± 2.0	13.0 ± 1.6	1.7 ± 1.6
D	6.5 ± 0.6	86.8 ± 22.9	0.62 ± 0.09	40.0 ± 6.0	28.1 ± 4.1	31.9 ± 5.6

**Table 3.** Concentrations of metals in surface soils adjacent to wood structures

Structure	Cr (mg/kg)			Cu (mg/kg)			As (mg/kg)		
	Mean±SD	Background	Background-corrected	Mean ± SD	Background	Background-corrected	Mean±SD	Background	Background-corrected
A (N=3)	79.9 ± 10.3	43.3 ± 6.4	36.6	63.8 ± 9.9	42.5 ± 0.7	21.3	6.67 ± 0.39	4.74 ± 0.25	1.93
B (N=3)	44.5 ± 3.9	45.7 ± 12.8	—*	27.9 ± 1.0	25.6 ± 5.9	2.30	6.16 ± 0.69	4.95 ± 0.84	1.21
C (N=3)	224 ± 171	156 ± 23	68.0	117 ± 46	96.9 ± 7.3	20.1	7.37 ± 4.94	3.23 ± 0.97	4.14
D (N=6)	32.5 ± 6.8	5.0 ± 2.6	27.5	49.9 ± 20.9	23.4 ± 4.1	26.5	41.7 ± 27.8	7.21 ± 0.94	34.5

\*The average background concentration was higher than that for the soil samples collected near structure.

The average background metal concentrations varied greatly with structures. The average chromium concentrations ranged from 5.0 mg/kg for structure D to 156 mg/kg for structure C, whereas the average copper concentrations ranged from 23.4 mg/kg for structure D to 96.9 mg/kg for structure C. The arsenic concentrations, in contrast, were within a relatively narrow range, between 3.23 and 7.21 mg/kg. Due to the large variations in background metal concentrations, the measured concentrations were corrected for background concentrations for each structure and metal. Thereafter, the background-corrected soil concentrations were compared with each other (Table 3). The metal concentrations at structure B showed the lowest increase for all of the metals. The concentrations at structure C indicated the highest elevation of chromium, whereas those at structure D showed the highest increases for both copper and arsenic.

Large variations of background-corrected surface soil concentrations adjacent to structures (Table 3) might be caused by several factors, such as the amounts of metals leached, the differences in soil physicochemical properties, and the ages of structures (Tyler and McBride, 1982; Masscheleyn et al., 1991). A possible explanation for the lowest increase in the three metals at structure B is that the logs covering the wall of the cabin might not be fully exposed to rainfall due to the presence of large trees over the structure, resulting in a lesser degree of leaching.

With some exceptions, it generally appears that

background-corrected metal concentrations near the newer structures (C and D) were higher than those near the older structures (A and B). This can be explained by the high initial leaching of the metals into soil and their subsequent migration to the vicinal soil. This result is consistent with the findings by Chirenje et al. (2003), who observed larger increases in the CCA metal concentrations in newer (0-5 years old) structures than in older (5-10 years old) structures. The very high elevation of arsenic (34.5 mg/kg) in the soil adjacent to structure D would have been caused not only by both the high clay content (31.9%), leading to strong adsorption of arsenic on the soil, but also by the relatively high OM content (0.85%).

Comparison of structures of different age (3 vs. 8 years) indicated that the metal concentration gradients were more obvious at the newer structures (C and D) than at the older structures (A and B), with a few exceptions (site 1 for structure D). A possible explanation for this is that the leaching of metal components occurs intensively within the initial years of outdoor use, usually within the first 2 years. After that initial period, metal leaching from wood diminishes, and the metals that are released into the soil migrate to neighboring areas, according to soil properties and the specific mobility of those metals in soil.

A previous study (Chirenje et al., 2003) on the distribution of metals in soils adjacent to CCA-treated

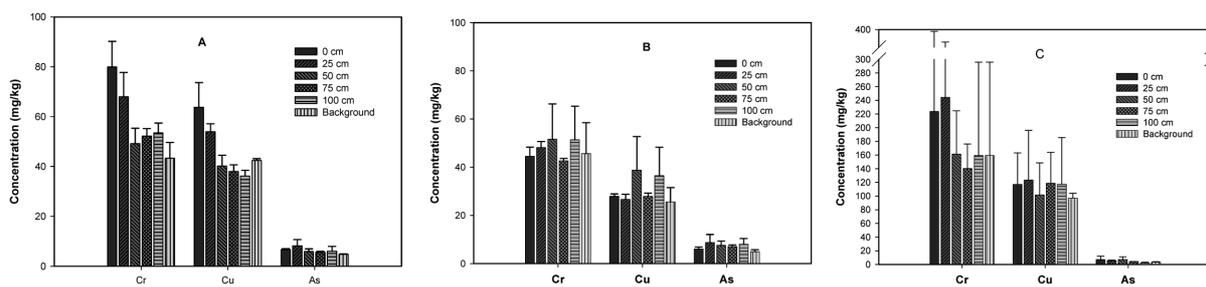


Fig. 1. Lateral distributions of chromium, copper, and arsenic in soils collected at log structures A, B, and C.

poles showed a result similar to this study. The authors classified soil samples into three groups according to the age of wood structures near soils (0-2, 2-5, and 5-10 years), and found that the newest group (0-2 years) revealed the largest increase in metal concentrations and also the clearest concentration gradients to 1.5 m, especially for arsenic. By contrast, soils around the oldest (5-10 years) poles did not show such an increase in metal concentrations, due to very limited recent leaching of metals from those poles.

### 3.3. Lateral distribution of metals

Fig. 1 shows the lateral distributions of chromium, copper, and arsenic at structures A, B, and C. It appeared that the chromium and copper concentrations at structure A increased at 0 and 25 cm compared with the background concentrations, whereas the arsenic concentrations seemed to distribute to 100 cm, indicating that arsenic migrates farther than the other two metals in soil. At structure B, the chromium and copper concentrations were not increased, but arsenic showed a slight concentration elevation at 25 to 100 cm, compared with the background concentrations. At structure C, the chromium and copper background concentrations were much higher than those at structures A and B (approximately 4 times higher for chromium, and 2.5 and 5 times higher, respectively, for copper). Chromium showed elevations at 0 and 25 cm, whereas copper did not exhibit such an increase. The arsenic concentrations were remarkably higher at 0 to 75 cm (7.32-4.32 mg/kg) than the background concentrations (average 3.23 mg/kg), indicating

again that arsenic, of the three metals, is the most mobile in soil.

At structure D, the lateral distributions of the three metals were investigated at three sampling sites (Fig. 2). At site 1, the chromium and arsenic distributions were limited within 20 cm, whereas copper did not show any apparent concentration gradient. At sites 2 and 3, the concentration gradients of all three metals were noticeable. At site 2, the chromium concentrations increased to the distance of 40 cm, whereas the copper and arsenic concentrations increased only to 20 cm. The arsenic concentrations were greatly elevated at 0 and 20 cm compared with the background concentration (7.3 mg/kg), showing 46.9 and 24.5 mg/kg, respectively. At site 3, the concentration increased within 60 cm for chromium, 20 cm for copper, and 40 cm for arsenic. However, the copper and arsenic concentration increases at site 3 were much higher than those at site 2.

The variations of the lateral distributions of the CCA metals reflect the varying mobility of metals in soil. Since copper in soil exists mostly in cationic forms, it is readily adsorbed on the soil surface, especially when organic ligands such as carboxylic and phenolic groups are abundant (Tyler and McBride, 1982; Tipping, 1993). Therefore, copper released into soil from CCA-treated wood tends to be confined within the vicinity of the structure unless the soil pH is high. Chromium in soil prevalently occurs as cationic ( $\text{CrOH}^{2+}$ ) at pH 2-6 or as neutral  $[\text{Cr}(\text{OH})_3]$  species at pH 6.5-11.5 (Sass and Rai, 1987). Contrastingly, arsenic in soil exists mostly in either neutral ( $\text{H}_3\text{AsO}_3$ ) or anionic form ( $\text{H}_2\text{AsO}_3^-$ ,  $\text{H}_2\text{AsO}_4^-$

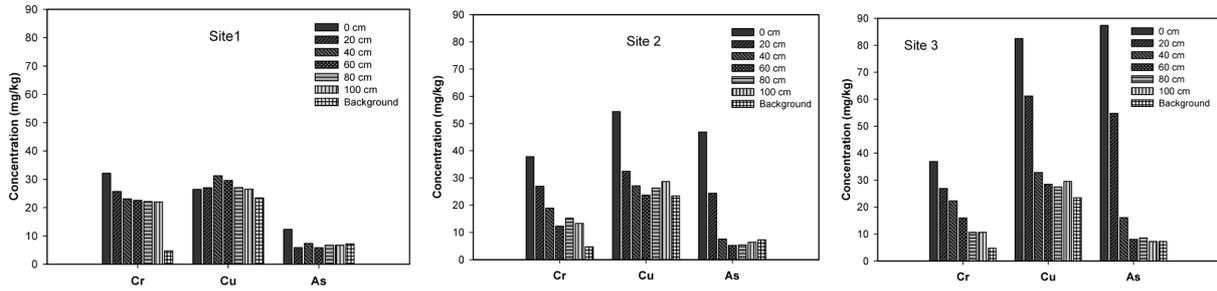


Fig. 2. Lateral distributions of chromium, copper, and arsenic in soils collected at three sound barrier (structure D) sites.

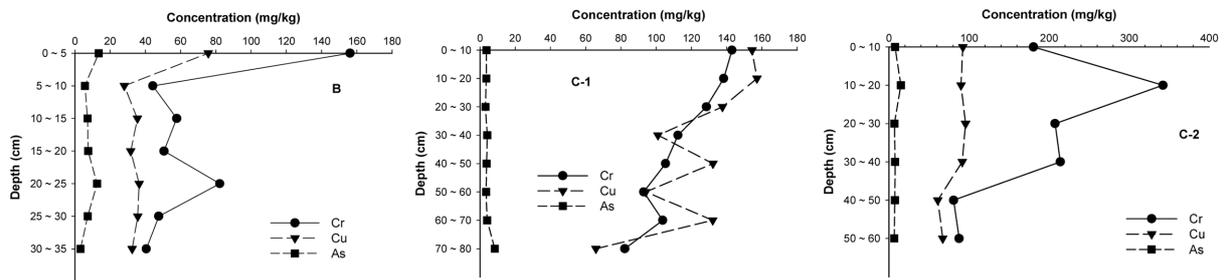


Fig. 3. Vertical distributions of chromium, copper, and arsenic in soils collected at log structures B and C.

or  $\text{HAsO}_3^{2-}$ ), and so its mobility in soil is reported to be higher than those of the other metals (Sadiqet al., 1983; Masscheleyn et al., 1991). However, Rahman et al. (2004) reported that of the three metals, chromium seemed to diffuse to the least extent.

**3.4. Vertical distribution of metal components**

Profile soil samples were collected from one site at structure B and from two sites at structure C. The metal concentrations decreased with depth at all three sites, even if the patterns varied (Fig. 3). At the structure B site, the three metal concentrations did not vary greatly, except at a depth of 0-5 cm. The concentrations were the greatest in the surface soil (0-5 cm), showing 156, 75.7, and 13.5 mg/kg for chromium, copper, and arsenic, respectively. At site 1 of structure C (C-1), the chromium and copper concentrations were elevated to the depths of approximately 50 and 20 cm, respectively. However, there was no obvious concentration gradient for arsenic at any depth, except at 70-80 cm. At site 2 of structure C (C-2), chromium and copper showed concentration gradients to approximately 40 cm, but arsenic showed

a narrower range of concentration distribution (10-20 cm).

The profile distributions of the metals at structure D differed from those at structures B and C (Fig. 4). At site D-1, chromium and copper appeared to show a concentration increase to 10 and 5 cm from the surface, respectively, whereas arsenic showed a concentration increase over the entire range of sampling depths, exhibiting similar concentrations between 10 and 25 cm. At site D-2, both the chromium and copper concentrations were elevated within 10 cm, whereas the arsenic concentrations were elevated to the depth of 25 cm. The copper concentrations rapidly diminished at a depth of 10-15 cm.

Vertical concentration gradients for all three metals (especially arsenic) have been observed more in soils collected near younger (0-2 years old) utility poles than in soils collected near older (2-5 and 5-10 years old) utility poles, within the sample collection range (0 and 60 cm) (Chirenje et al., 2003). This behavior was explained in reference to the ongoing leaching of metal components into the surrounding soil from the younger poles. Even in a highly contaminated abandoned wood preservation unit in Sweden (the mean Cr, Cu,

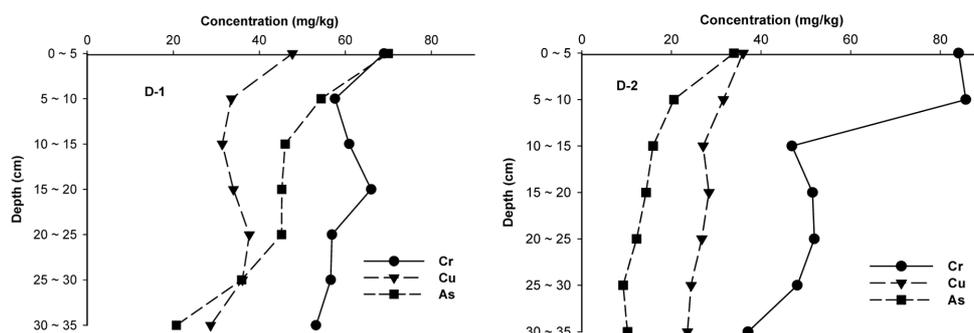


Fig. 4. Vertical distributions of chromium, copper, and arsenic in soils collected at two sound barrier (structure D) sites.

and As concentrations in the surface soils were 29, 26, and 186 mg/kg, respectively), decreases in the concentrations of the three metals in the soil profile samples were limited to a depth of 30 cm (Bhattacharya et al., 2002), indicating the limited migration of leached metals in soil.

#### 4. Conclusions

The results obtained from this study on the spatial distributions of CCA metals in soil around three log structures and a sound barrier proved that chromium, copper, and arsenic are released from treated wood and contaminate neighboring soils both laterally and vertically. Metal concentrations around newer structures showed clearer gradients than those around older structures, indicating that more CCA metals are leached into soil in the course of initial outdoor use and migrate to vicinal soil over time.

The lateral distribution results showed that the chromium and arsenic concentration gradients were observed to 60 and 100 cm, respectively. However, the copper concentration gradients were limited to 20 cm. Even though the vertical distributions of the three metals were not as clear as the lateral distributions, it was evident that the metals had also migrated vertically. However, it seems that CCA metals are confined to a limited distance both laterally and vertically. Therefore, it is not likely that these metals, after they leach into soil, can contaminate ground water.

During the last few years, many CCA-treated log

cabins have been built in mountain rest areas in Korea. Moreover, CCA-treated wood has been used even indoors on the walls and ceilings of some of these structures. Therefore, direct human contact with those wood surfaces can cause the transfer of CCA metals to the skin. The results of this study suggest that further research is needed for a fuller appreciation of the possible impacts of CCA-treated wood on humans and ecosystems.

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#### References

- Bendor, A. and Banin, E., 1989, Determination of organic matter content in arid-zone soils using a simple "loss-on-ignition" method, *Soil Sci. Plant Anal.*, **20**, 1675-1696.
- Bhattacharya, P., Mukherjee, A.B., Jacks, G., and Nordqvist, S., 2002, Metal contamination at a wood preservation site: characterization and experimental studies on remediation, *Sci. Total Environ.*, **290**, 165-180.
- Blassino, M., Solo-Gabriele, H., and Townsend, T., 2002, Pilot scale evaluation of sorting technologies for CCA treated wood waste, *Waste Manage. Res.*, **20**, 290-301.
- Bouyoucos, G.J., 1936, Directions for making mechanical analysis of soils by the hydrometer method, *Soil Sci.*, **4**, 225-228.
- Breslin, V.T. and Adler-Ivanbrook, L., 1998, Release of copper, chromium and arsenic from CCA-treated lumber in estuaries, *Estuar. Coast. Shelf Sci.*, **46**, 111-125.

- Chirenje, T., Ma, L.Q., Clark, C., and Reeves, M., 2003, Cu, Cr and As distribution in soils adjacent to pressure-treated decks, fences and poles, *Environ. Pollut.*, **124**, 407-417.
- Cooper, P.A., 1991, Leaching of CCA from treated wood: pH effects, *Forest Prod. J.*, **41**, 30-32.
- Fleming, H.D. and Ide, R.G., 1976, Determination of volatile hydride-forming metals in steel by atomic absorption spectrometry, *Anal. Chim. Acta*, **83**, 67-82.
- Gezer, E.D., Yildiz, Ü.C., Temiz, A., Yildiz, S., and Dizman, E., 2005, Cu, Cr and As distribution in soils adjacent to CCA-treated utility poles in Eastern Blacksea region of Turkey, *Build. Environ.*, **40**, 1684-1688.
- Hingston, J.A., Collins, C.D., Murphy, R.J., and Lester, J.N., 2001, Leaching of chromated copper arsenate wood preservatives: a review, *Environ. Pollut.*, **111**, 53-66.
- Jones, J.B., 2001, Laboratory Guide for Conducting Soils Tests and Plant Analysis, CRC Press, New York, pp. 32-33, 143-144, **152**, 159-160.
- Kartal, S.N., Hwang, W.-J., and Imamura, Y., 2007, Evaluation of effect of leaching medium on the release of copper, chromium, and arsenic from treated wood, *Build. Environ.*, **42**, 1188-1193.
- Kim, H., Kim, D.-J., Koo, J.-H., Park, J.-G., and Jang, Y.-C., 2007, Distribution and mobility of chromium, copper, and arsenic in soils collected near CCA-treated wood structures in Korea, *Sci. Total Environ.*, **374**, 273-281.
- Kim, H., Kim, D.-J., Park, J.-G., Shin, Y.S., Hwang, I.Y., and Kim, Y.K., 2006, Distribution of chromium, copper, and arsenic in soils adjacent to steps, a deck, and a sound barrier constructed with a wood preservative CCA-treated timbers, *J. Kor. Soc. Soil Groundwat. Environ.*, **11**, 54-64.
- Lebow, S., Foster, D., and Evans, J., 2004, Long-term soil accumulation of chromium, copper, and arsenic adjacent to preservative-treated wood, *Bull. Environ. Contam. Toxicol.*, **72**, 225-232.
- Lebow, S. and Foster, D., 2005, Environmental concentrations of copper, chromium, and arsenic released from a chromated-copper-arsenate-(CCA-C-) treated wetland boardwalk, *For. Prod. J.*, **55**, 62-70.
- Lebow, S.T., Foster, D.O., and Lebow, P.K., 1999, Release of copper, chromium, and arsenic from treated southern pine exposed in seawater and freshwater, *For. Prod. J.*, **49**, 80-89.
- Masscheleyn, P.H., Delaune, R.D., and Patrick, W.H., 1991, Effect of redox potential and pH on arsenic speciation and solubility in a contaminated soil, *Environ. Sci. Technol.*, **25**, 1414-1419.
- Rhaman, F.A., Allan, D.L., Rosen, C.J., and Sadowsky, M.J., 2004, Arsenic availability from chromated copper arsenate (CCA)-treated wood, *J. Environ. Qual.*, **33**, 173-180.
- Robinson, B., Greven, M., Green, S., Sivakumaran, S., Davidson, P., and Clothier, B., 2006, Leaching of copper, chromium and arsenic from treated vineyard posts in Marlborough, New Zealand, *Sci. Total Environ.*, **364**, 113-123.
- Sadiq, M., Zaidi, T.M., and Mian, A.A., 1983, Environmental behaviour of arsenic in soils: theoretical. *Water Air Soil Pollut.*, **20**, 369-377.
- Sass, B.M. and Rai, D., 1987, Solubility of amorphous chromium(III)-iron(III) hydroxide solid solutions, *Inorg. Chem.*, **26**, 2228-2232.
- Stilwell, D.E. and Gorny, K.D., 1997, Contamination of soil with copper, chromium, and arsenic under decks built from pressure treated wood, *Bull. Environ. Contam. Toxicol.*, **58**, 22-29.
- Stilwell, D.E. and Graetz, T.J., 2001, Copper, chromium, and arsenic levels in soil near highway traffic sound barriers built using CCA pressure-treated wood, *Bull. Environ. Contam. Toxicol.*, **67**, 303-308.
- Tipping, E., 1993, Modelling ion-binding by humic acids, *Coll. Surf. A: Physicochem. Eng. Asp.*, **73**, 117-131.
- Townsend, T., Solo-Gabriele, H., Tolaymat, T., Stook, K., and Hosein, N., 2003, Chromium, copper, and arsenic concentrations in soil underneath CCA-treated wood structure, *Soil Sed. Contam.*, **12**, 779-798.
- Townsend, T., Stook, K., Tolaymat, T., Song, J.K., Solo-Gabriele, H., Hosein, N., and Khan, B., 2001, *New lines of CCA-treated wood research: in-service and disposal issues*, Technical Report 00-12, Florida Center for Hazardous Waste.
- Tyler, L.D. and McBride, M.B., 1982, Mobility and extractability of cadmium, copper, nickel and zinc in organic and mineral soil columns, *Soil Sci.*, **134**, 198-205.
- U.S. EPA., 1998, EPA Method 3051A-Microwave Assisted Acid Digestion of Sediments, Sludges, Soils, and Oils.
- Zagury, G.J., Sampson, R., and Deschénes, L., 2003, Occurrence of metals in soil and groundwater near chromated copper arsenate-treated utility poles, *J. Environ. Qual.*, **32**, 507-514.