

Extraction of heavy metals from contaminated soil by *Cinnamomum camphora*

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Abstract 83 acres of rice paddy fields in Taoyuan county, Taiwan, were polluted by cadmium (Cd), chromium (Cr) and copper (Cu) through a nearby irrigation channel, and rice plantation was ceased in 1987. Camphor trees (*Cinnamomum camphora*) have been planted in 2 acre of the above fields since 1991. Heavy metal accumulation of roots, leaves, branches and heartwood of camphor trees were analyzed during 20-year afforestation. Averaged Cd contents of the roots were found larger than the ones of the branches, leaves, sapwood and heartwood of camphor trees growing in three polluted plots. Averaged diameters at breast height (DBH) of the planted camphor trees were 13–15 cm. Cd pollution did

not significantly impact the growth of camphor trees, as similar DBH's were found from both polluted and control sites. Annual growths of DBH were from 0.63 to 0.77 cm year⁻¹. Planting camphor trees sequestered 68.8 ton biomass per acre. During 20-year period, 0.69–1.98 ton C year⁻¹ ha⁻¹ were sequestered on three polluted plots. The above numbers exceeded IPCC LULUCF reference values 0.31–0.53 ton C year⁻¹ ha⁻¹ for activities at forest lands.

Keywords Heavy metals · Remediation · Cadmium · Carbon sequestration · Groundwater pollution · *Cinnamomum camphora*

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Introduction

Heavy metals are trace elements, like cadmium, mercury, lead, arsenic, zinc and nickel, derived from industrial activities, mining and the generation of municipal wastes. Improper disposal of heavy metals have result the worldwide release of large amounts of potentially toxic compounds (Lasat et al. 1998; Kabata-Pendias 2001). Soil contamination by heavy metals is one of the major environmental problems raising critical concerns for both human health and ecosystems (Kabata-Pendias 2001), due to their carcinogenic and mutagenic effects (Baudouin et al. 2002).

Various physical, chemical, and biological processes are currently being used to remediate metal-contaminated soils. Phytoremediation is the in situ application of plants and their associated microflora for environmental cleanup. This technology makes use of the naturally occurring processes by which plants and their microbial rhizospheric flora degrade and sequester organic and inorganic pollutants (Pilon-Smits 2005). Despite its obvious advantages, the effectiveness of phytoremediation must be confirmed to

validate its use in practical remediation. Such criteria have the ability to remove or neutralize contaminants and time effectiveness need to be evaluated. The technology depends on the level and the types of metals and their chemical forms, the uptake and endurance capability to tolerate metal accumulation without phytotoxic effects of the plants, the biomass production capacity of the harvested crop and the final level of heavy metals in the soil to be considered remediated (McGrath 1998; Yadav et al. 2010). Previous studies have shown that Cr and Pb are not easily transferred to aerial plant biomass as they are mainly stored in root cells (Mellem et al. 2009; Tiwari et al. 2009; Yu et al. 2010), whereas Zn is easily accumulated in green tissues like leaves (Probst et al. 2009; Liu et al. 2011).

Due to the fast development of small to mid-scale entrepreneurship, the economy of Taiwan was experiencing a rapid growth during 1970 and 80's. Many small factories were set up among or adjacent to the surrounding rice paddy fields due to loosely enforced land use regulations. Unfortunately, there were several incidents involved the illegal dumping of heavy metal containing wastewater polluting nearby rice paddy fields through irrigation systems at that era. In 1982, cadmium (Cd) pollution exceeding 5 mg/kg soil was detected for few rice paddies in Taoyuan county, Taiwan. A nearby plastic plant dumping wastewater containing plasticizer formulated with cadmium stearate was found responsible. After a more extensive survey, the plantation of additional 83 acres of rice paddies was suspended. Since 1991, camphor trees (*Cinnamomum camphora*) have been planted in 2 acres of the above fields. Camphor tree, a native species, was selected due to its adaptability to wide varieties of weather patterns and soil types (Taiwan Forest Bureau 2006). Semi-aquatic rice paddies require clayey soils with low hydraulic conductivities, precluding plantation of many other tree species. Camphor lumber of large diameters could have good market perspective. Farming of identified polluted rice paddy fields has been long ceased. Nevertheless, intensive monitoring of polluted sites is being enforced with plans of remediation being set up. Heavy metal accumulation of leaves, branches sapwood and heartwood of camphor trees during 20-year afforestation were analyzed, as well as their biomass accumulation. Since the activity of the present study involved land-use change from cropland to forest land, carbon sequestration potentials were compared with the values estimated by the land-use change and forestry (LULUCF) report by IPCC (IPCC 2000).

Materials and methods

Plot description and sampling schedules

There were seven plots investigated in this study, as their relative positions depicted in Fig. 1 with the defunct plastic

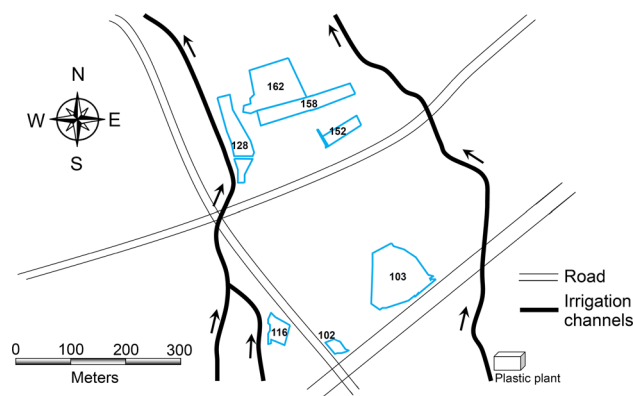


Fig. 1 Schematics of locations for plots and the source of pollution

plant in the upstream of the study plots. Cd exceeding 5 mg/kg were found in soil layers among 0–30 cm in the plot 103 (10,930 m²), 152 (1,763 m²), 162 (8,196 m²), 102 (282 m²), 158 (5,172 m²) and 116 (2,007 m²) in 1987. Then the ban of rice plantation of above plots was imposed for food safety reason. Although there was no exceeding Cd detected, rice plantation was also ceased for the plot 128 (3,548 m²) as market demand dwindled for rice from that area. Camphor trees were planted in plot 103, 152, 162 and 128. The analytical data from trees in plot 128 serve as the control group in this study. Soil sampling was conducted in October, 2010. Survey of camphor tree community of the four plots was conducted from November to December, 2010. Tree falling was conducted from March to April, 2011. Sampling was conducted in at least triplicate for each plot.

Soil sampling and analysis

Soil samples were collected at 0–15 and 15–30 cm depth and kept at 4 °C before drying. Soil samples were dried in an oven at 105 °C for 24 h, then crushed and sieved to 2 mm. Soil pH was determined with a glass electrode in distilled water and in soil suspensions at a 2:1 soil to liquid ratio. Total organic carbon (TOC) was analyzed by the Walkley-Black method. Available phosphorus (P_{ava}) was determined by UV/Vis spectrophotometry on sodium bicarbonate/sodium hydroxide soil extracts according to the Olsen method. To determine the total contents of heavy metals, dry soil samples were subjected to microwave assisted digestion with a Suprapure[®] HNO₃:H₂O₂:HCl mixture (7:1:1 v/v). The total concentrations of heavy metals in soil were determined using inductively coupled plasma atomic emission spectroscopy.

Biomass survey, sampling and analysis

Survey of all camphor tree and barnyard weed in the seven plots was conducted to estimate aboveground biomass

accumulation and carbon sequestration by camphor tree and by barnyard weed. Contents of carbon fixed (CF) were calculated by diameter at breast height (DBH) and height values from the trees surveyed in the sampling plots based on previously published procedure (Wang 2011). Fresh leaves and living barks were hand-picked. Secondary branches were randomly sampled as the branch specimens. Harvesting of camphor trunk was shown in the picture as an electronic supplement. Camphor trees demonstrated a distinctive pattern for heartwood and sapwood. Trunks at breast height (BH), 30 cm below and above BH were collected and mixed by equal weight portions for metal analysis. Ten 3 g samples of each portion from each fallen camphor tree were collected and mixed for analysis. Barnyard weed was harvested within the area of one square meter. The collected specimens were carefully washed with deionized water, and then dried for 72 h at 70 °C. The tissues were grinded into powder passing no. 60 meshes, ground into a fine powder using an acid-washed porcelain mortar and pestle and fully mineralized with 5 ml HNO₃ 70 % (w/v) in a microwave oven. After dilution to a final concentration of 3.5 % HNO₃, metal concentration was determined using inductively coupled plasma atomic absorption spectroscopy (ICP-AES).

Results and discussion

Soil characteristics

The properties of surface soils in the study area are shown in Table 1. Soil pH in woodland and weedland samples was about 5.57–5.84 and 5.30–6.35, respectively. Soil pH sampled from the control sites was around 5.66. The weedland soils had lower water content than woodland soils and control sites. Soil EC in woodland and weedland samples was about 24.55–29.72 and 22.90–39.25 $\mu\text{S}/\text{cm}$, respectively. Soil EC sampled from the control sites was around 28.09 $\mu\text{S}/\text{cm}$. Soil total C in woodland and weedland samples was about 1.28–1.82 and 0.76–2.09 %, respectively. Soil total C sampled from the control sites was around 1.63 %. However, the weedland soils, plot 116, had higher particle size of than the soils of woodland and control sites. Weedland soils had relatively low cation exchange capacities (CEC) from 10.01 to 12.00 cmol cation/kg, than the values of woodland soils and control soils. All of soils from the woodland, weedland and control sites mainly belong to clay texture with small amounts of sand and silt.

Heavy metal contents of soils

Table 2 showed the heavy metal contents of the soils in the woodland, weedland and control plots. The most averaged

soil Cd concentrations in the woodland and weedland plots were higher than control plots for both depths. The observed highest soil Cd concentrations were 7.42 and 11.14 mg/kg in the layer 0–15 and 15–30 cm for plot 158. However, after examined by post hoc LSD analysis, only soil Cd contents of woodland plot 103 (both depths) and weedland plots 102 (15–30 cm) and 158 (both plots) differed from soil Cd contents from the control plots for both depths. Soil Cd contents of woodland plot 103 (15–30 cm) and weedland plot 158 (both depths) were found statistically higher than the other analyzed soil Cd contents. On the other hand, the soil Cd contents for both depths of weedland plot 116 were found statistically lower than the other measured soil Cd contents. The above finding revealed that the soil Cd concentrations of current study site still preclude its farming usage now. Because soil concentrations exceeding 2.5 mg Cd/kg soil mandates continuous monitoring programs, and soil concentrations exceeding 5 mg Cd/kg soils mandates active control measures based on Taiwan EPA groundwater pollution control regulations for food stock production farmlands.

The averaged soil Cr contents were around 35–40 mg/kg soil for all plots. Table 2 showed there weren't significant difference between soil Cr contents for all plots, except contents of 0–15 cm samples for woodland plots 103 and 152. The above Cr values are less than the continuous monitoring standard at 175 mg Cr/kg soil for farmland. The averaged soil Cu contents were around 16.35–37.2 mg/kg soil for all polluted plots. Table 2 showed there weren't significant difference between soil Cu contents for all plots, except the highest Cu contents for weedland plot 158. Averaged 0–15 and 15–30 cm soil Cu contents of control plot 128 were generally less than the values of the woodland and weedland plots, but not significantly different from the polluted plots after examined by post hoc LSD analysis. The above Cu values are less than the continuous monitoring standard at 120 mg Cu/kg soil for farmland.

The distribution of soil heavy metal contents was consistent with the study site since 20 years ago: mainly soil Cd pollution with associated Cr and Cu pollutions at lesser extents. Although a lesser pollution the control plot 128 was found, it might be still polluted due to sharing an identical irrigation system with other plots.

Heavy metal contents of different parts of camphor trees

The heavy metal contents of different parts of camphor trees varied with the metal and the portions as depicted in Fig. 2. The averaged Cd concentrations, from 0.75 to 10.63 mg/kg, were in the following order: roots, branches, leaves, sapwoods and, heartwoods for the camphor trees in

Table 1 Soil texture

Plot	pH (–)	Water (%)	Temp. (°C)	EC (μS/cm)	Total C (%)	Particle size (mm)	CEC (cmolc/kg)	Texture
Woodland								
103	5.57 ± 0.37	4.18 ± 1.74	25.09 ± 0.22	29.72 ± 7.77	1.82 ± 0.92	0.12 ± 0.07	12.17 ± 2.56	Clay
152	5.84 ± 0.11	3.14 ± 0.68	25.06 ± 0.26	28.44 ± 13.24	1.58 ± 1.24	0.10 ± 0.02	10.88 ± 2.62	Clay
162	5.68 ± 0.18	4.73 ± 1.47	25.23 ± 0.16	24.55 ± 2.96	1.28 ± 1.08	0.11 ± 0.02	12.93 ± 4.14	Clay
Weedland								
102	5.30 ± 0.14	2.95 ± 0.21	25.05 ± 0.64	39.25 ± 0.64	2.09 ± 1.00	0.11 ± 0.02	12.00 ± 2.26	Clay
116	6.35 ± 0.13	2.48 ± 0.53	25.88 ± 1.56	22.90 ± 4.99	0.76 ± 0.37	0.72 ± 0.34	10.01 ± 2.58	Clay
158	5.85 ± 0.23	3.77 ± 0.84	24.87 ± 0.27	28.18 ± 4.85	1.62 ± 0.81	0.11 ± 0.02	11.14 ± 2.23	Clay
Control								
128	5.66 ± 0.3	4.10 ± 1.55	25.12 ± 0.22	28.09 ± 8.3	1.63 ± 1.01	0.11 ± 0.05	12.09 ± 2.99	Clay

Table 2 Soil heavy metals content

Plot	Cd (mg/kg)		Cr (mg/kg)		Cu (mg/kg)	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Woodland						
103	4.28 ± 1.20	4.31 ± 3.00	43.22 ± 10.82	41.02 ± 1.12	28.04 ± 18.74	23.84 ± 10.8
152	3.17 ± 0.31	2.31 ± 0.39	33.71 ± 0.19	36.74 ± 0.32	18.71 ± 0.90	16.35 ± 0.13
162	2.13 ± 1.00	1.87 ± 1.21	36.77 ± 1.11	39.30 ± 1.85	18.33 ± 1.78	18.33 ± 2.57
Weedland						
102	3.04 ± 0.11	3.78 ± 0.06	37.05 ± 0.53	40.79 ± 0.80	16.89 ± 0.57	14.79 ± 0.33
116	0.51 ± 0.06	0.14 ± 0.07	35.66 ± 0.44	35.03 ± 0.52	22.64 ± 0.56	30.73 ± 0.58
158	7.42 ± 1.86	11.14 ± 3.86	38.80 ± 2.75	41.00 ± 3.38	37.20 ± 19.68	35.33 ± 12.53
Control						
128	1.21 ± 0.62	0.73 ± 0.37	41.63 ± 5.93	40.76 ± 4.11	17.66 ± 0.91	11.07 ± 0.61

polluted plots for Cd. Post hoc LSD analysis revealed that root Cd concentrations for camphor trees plots were different from the Cd concentrations of heartwood for all four plots. The order of Cu accumulations in all compartments are identical to the findings for willows (*Salix* sp.) grown in a sediment disposal site (Meers et al. 2005). Metal concentrations in the branches were statistically similar to the values of roots.

Averaged Cr concentrations of all compartments were found from 1.41 to 22.11 mg/kg for all three contaminated plots, and the root Cr contents were higher than others. While the averaged Cr concentrations of all four compartments for control plot 128 were lower than the respective values of for all three contaminated plots. However, Post hoc LSD analysis revealed that root Cr concentrations couldn't be distinguished from the values of other compartments. The present study did not exhibit the high Cr enrichment in the root like 4-year grown willows (*Salix* sp.) grown in a sediment disposal site (Meers et al. 2005). Due to the 20-year growth for the camphor tree in this study, Cr might achieve more even distribution. Compared with loamy soils for the willows (Meers et al.

2005), clayey soils in the present study might limit the availability of soil Cr for the camphor tree.

Averaged Cu concentrations of all compartments were found from 2.5 to 18.05 mg/kg for all three contaminated plots, with compartment concentrations at the order as leaves, branches, roots, sapwoods and heartwoods. Although the averaged Cu concentrations of all four compartments for control plot 128 were lower than the respective values of for all three contaminated plots, the order between compartments remained as same. Post hoc LSD analysis revealed that Cu concentrations of root and leaves were significantly higher than values of heartwood and sapwood. The present study demonstrated identical Cu uptakes range and orders among four compartments as ones of 4-year grown willows (*Salix* sp.) grown in a sediment disposal site (Meers et al. 2005). The ranges of soil Cu distribution in the present study were also identical to the respective values of a previous study (Meers et al. 2005).

Potentials of camphor tree uptake based on initial soil heavy metal contents are illustrated through the concentration factors (CF), which are listed in Table 3. CF is defined as the ratio of heavy metal concentration in the

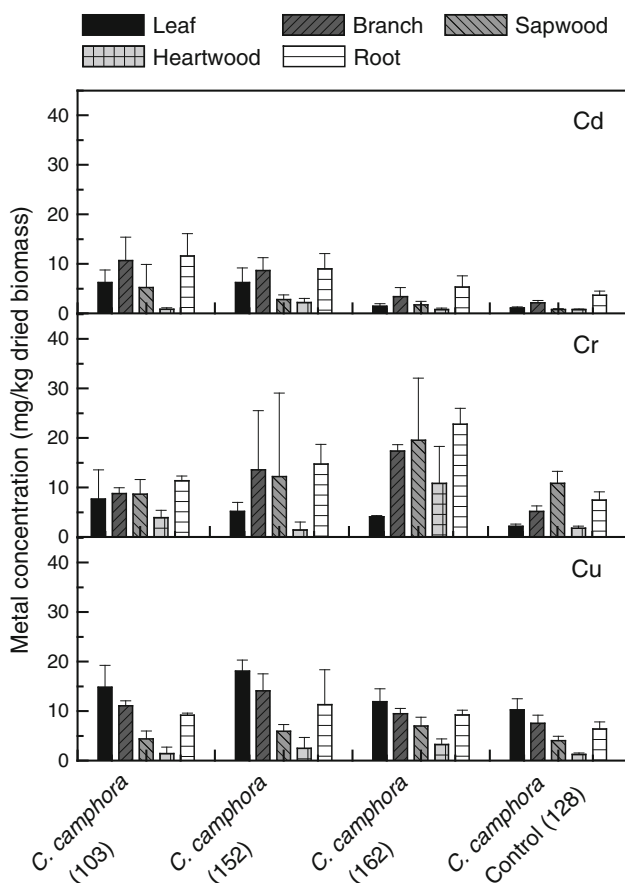


Fig. 2 Metal concentrations of individual tree compartments for each plot

biomass to the values in the soil based on dried weight in the present study. The highest concentration factors of camphor trees were: 2.66 for Cd in root, 0.44 for Cr in root, and 0.71 for Cu in leaf. The higher concentration factor indicates that camphor trees retain metals in the roots and biomass, and limit the mobility of metal toward the surrounding soil environments. Even though Cd contents of each compartment were lower than the values of other two metals shown by Fig. 2, Table 3 showed the branch and leaves of the camphor trees had CF values larger than the unity. That implies that harvesting branches and leaves of camphor trees could be one viable option to achieve phyto-remediation for Cd. CF values less than 1 indicates that heartwood and sapwood could be safely applied to serve as timber and biomass fuel. Although camphor trees couldn't concentrate much Cr and Cu, they still could uptake some metals and adapt to the soil environment of the present study.

CF values of other woody species from the literatures are also listed for comparison, although there are so many factors affect tree metal uptakes like: soil, plant adaptability (McIntyre 2003), phylogenetic and morphological

diversities. Table 3 showed a great variety for CF values among different species, as well as among *Salix* genotypes (Maxted et al. 2007). Among tree species listed in Table 3, *Salix* spp., *Populus* spp., *Betula* spp., *Rosemarinus* spp., are common in temperate climate areas, while carambola (*Averrhoa carambola*) and camphor trees are common in subtropical and tropical climate areas. Ages of most the trees listed in Table 3 were less than 5-year. In Table 3, the lowest CF values for 1-year cutting for *Salix* leaf and stem were found at a site with historically amended sewage sludge in UK (Maxted et al. 2007). Lower CF values 3-year cutting for *Salix* and *Betula* stems were also found at sites for historical sludge disposal in UK (French et al. 2006). Loamy soils (Meers et al. 2005; Li et al. 2009) and freshly mixed sludge (Dimitriou et al. 2006) resulted higher tree CF values due to a greater metal availability than the present study. Differences among species could result a great variety of CF values even at a same site (Domínguez et al. 2008). CF values of 4-year seedling of carambola (*A. carambola*) decreased from 3-year seedlings (Li et al. 2009). The above finding suggested that the carambola biomass growth dominated Cd uptake after initial fast growing period. After comparison with the above studies, camphor trees in the present study revealed remarkable Cd uptakes after 20 years of plantation in clayey soils polluted by a single incident 20 years ago.

Biomass accumulation in the 20-year growth period

The amounts of biomass and carbon sequestered by different parts of camphor trees in the sampling plots are summarized in Table 4. There were 68.8 ton camphor biomass (dry based) recorded on 2.089 ha of three polluted plots, including both aboveground and root portions. The averaged aboveground expansion factor was 1.3, similar to a previous survey for camphor trees in Taiwan (Lee and Feng 2010). Lower planting densities allowed crown developments in the present study. Averaged belowground expansion factor was 1.28, less than 1.4 of the previous survey for camphor trees in Taiwan (Lee and Feng 2010). Since camphor trees grown clayey paddy fields in the present study, dense soil structure might more or less restrict the root development.

There were 633, 388 and 869 camphor trees surveyed in the plot 103, 152 and 162, respectively. Tree DBH values were 15.4 ± 5.5 , 12.6 ± 4.9 and 13.5 ± 6 cm for camphor trees surveyed in the plot 103, 152 and 162, respectively. In the control plot 128, 204 camphor trees were surveyed. In the control plot 128, DBH of 15.2 ± 5.2 cm for camphor trees were surveyed. The converted population densities for camphor trees were 606, 1059, 2204 and 680 (stems per acre) for the plot 103, 131, 152 and 128, respectively. The DBH values of camphor trees in three contaminated plots

Table 3 Concentration factor for Cd, Cr, and Cu of tree species

Region	Concentration factor			Reference
	Cd	Cr	Cu	
<i>Cinnamomum camphora</i>				This study
Leaf	1.34 ± 0.64	0.15 ± 0.03	0.71 ± 0.23	
Branch	2.24 ± 0.58	0.27 ± 0.05	0.56 ± 0.18	
Sapwood	0.96 ± 0.23	0.21 ± 0.45	0.28 ± 0.12	
Heartwood	0.41 ± 0.25	0.14 ± 0.06	0.12 ± 0.06	
Root	2.66 ± 0.14	0.44 ± 0.18	0.48 ± 0.14	Meers et al. (2005)
<i>Salix viminalis</i>				
Wood	1.67	3.64	0.33	
Bark	2.00	5.82	0.45	
Leaf	2.67	10.73	0.56	
Root	11.00	10.18	0.49	Domínguez et al. (2008)
<i>Populus alba</i>				
Leaf	2.46		0.07	
<i>Rosmarinus officinalis</i>				French et al. (2006)
Leaf	0.03		0.12	
<i>Salix viminalis</i> × <i>schwerinni</i> ‘Tora’				Maxted et al. (2007)
Stem	0.70		0.07	
Foliar	1.25		0.05	
<i>Betula pendula</i> Roth.				Li et al. (2009)
Stem	0.16		0.02	
Foliar	0.08		0.03	
<i>Salix dasyclados</i>				Dimitriou et al. (2006)
Leaf	0.44			
Stem	0.20			
<i>Salix viminalis</i>				Dimitriou et al. (2006)
Leaf	0.08			
Stem	0.07			
<i>Averrhoa carambola</i>				Dimitriou et al. (2006)
Leaf	6.25			
Stem	6.25			
Root	1.88			
Twig	6.25			Dimitriou et al. (2006)
<i>Salix viminalis</i>				
Leaf litter	4.74		0.32	
wood	2.11		0.06	
bark	7.37		0.13	

Table 4 Biomass and carbon sequestered by different parts of camphor trees in the plots

	Plot number	Area (ha)	Camphor population in the plot	Trunk volume (m ³)	Trunk biomass (ton)	Twig biomass (ton)	Total biomass (ton)	Total carbon fixed (ton)
Woodland	103	1.093	663	56.5	20.9	5.0	32.3	16.2
	152	0.176	388	24.4	9.0	2.1	14.0	7.0
	162	0.820	869	39.3	14.6	3.5	22.5	11.3
Control	128	0.355	204	17.0	6.3	1.5	9.7	4.9

were significantly different from each other, as examined by the least significant difference post hoc analysis.

Table 2 indicated that the heavy metal concentrations of the soil layer up to 30 cm for plot 103 were higher than the values of the control plot 128. However, insignificant difference between of the camphor tree DBH values of the plot 103 and 128 was also revealed by the post hoc analyses. The roots of camphor trees reached up to depths of 60 cm during field observation, so the tree heavy metal uptakes may not be so significant at the later stage of growth. Heavy metal mobilization was less likely due to the low hydraulic conductivity, since the soils of all plots were found clayey as listed in Table 1.

On the other hand, the trend of DBH distribution followed the order of planting density among three contaminated plots. Total biomasses were 48.8 and 47.8 kg per stem for trees in plots 103 and 128, much larger than 36.0 and 25.9 kg per stem for trees in plots 162 and 152 with larger planting densities. Above observations demonstrated that the classical tree size density relationship (Drew and Flewelling 1979) dictated the camphor tree growth among four study plots, despite the significant differences among Cd concentrations of soils listed in Table 2. It suggested that the level of differences between soil Cd contents in polluted plots and control plot couldn't affect growth of the camphor trees in the present study.

Heavy metal impacts on carbon sequestration and long term growth

To elucidate the impact of soil heavy metal accumulation on the long term grown of camphor tree, the growth data were employed to compare with the data from 40 permanent camphor sample plots in the plantation forests established from 1910 to 1980 by Taiwan Forest Bureau. The plots were set up with official written records including DBH, tree heights, crown spans and planting densities; and they were located mostly in the hillsides at the altitudes below 500 m. Last biomass survey was conducted in 2006 (Lee and Feng 2010). Figure 3 shows the averaged DBH distribution with respect to ages. However, there was no clear trend between DBH distribution and the age of growth. Highest observed DBH was 37 cm of a 52-year old plot. DBH values were as low as 8 cm and 15 cm for an 84-year and 71 year old plots. There were so many factors effecting the growth of camphor trees, such as genotype and phenotype differences, soil characteristics, site characteristics and planting densities. Original purpose of clayey soil in the present study was rice farming. So the soil was naturally more fertile than the long term plantation forests on the hill side. To normalize the weather impact, only data from the sites below of altitude of 500 m were employed to be analyzed.

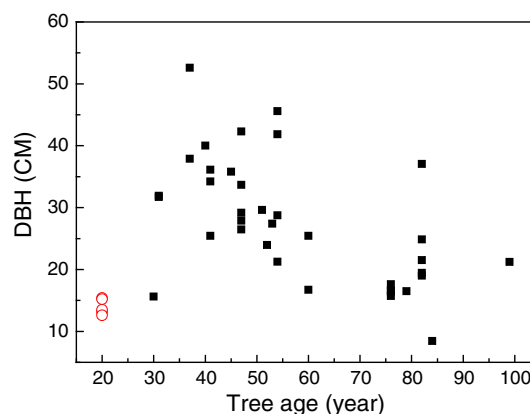


Fig. 3 Diameter at breast height (DBH) of the camphor permanent sampling plots (filled black square) and the plots of the present study (closed red circle) (Color figure online)

To further analyze long term growth of camphor tree on four plots, stem densities and length of growth periods from 40 long-term permanent camphor sample plots were employed to quantitatively compare by annual and per stem basis. Figure 4 shows the annual incremental DBH ($\text{cm}^1 \text{yr}^{-1}$), annual total carbon uptake ($\text{ton}^1 \text{year}^{-1} \text{ha}^{-1}$) and total C uptake per stem ($\text{kg}^1 \text{yr}^{-1} \text{stem}^{-1}$). Data from the present study are shown in left panels, while data from the camphor permanent sample plots are shown in right panels. The annual incremental DBH values were 0.77 ± 0.27 , 0.67 ± 0.30 , 0.63 ± 0.25 ($\text{cm}^1 \text{year}^{-1}$) for plots 103, 162 and 152 showed in the up-left panel of Fig. 4. For the control plot 128, the annual incremental DBH value was 0.77 ± 0.27 . Despite different Cd levels in soils (Table 2) and in tree root, branches and leaves (Fig. 2) for both plots, statistically identical annual incremental DBH values were found for plots 103 and control plot 128. Higher plant densities resulted less annual DBH increment of camphor trees among four plots. The declining trend was more obvious for 40 permanent camphor sample plots showed in the top-right panel of Fig. 4. Weakly negative correlations could be attributed to different site conditions for other camphor permanent sample plots. The camphor tree growths of the present study plots with lower plant densities were comparable to ones of permanent sample plots. The camphor tree growths of the plot 152 with the highest densities were better than ones of permanent sample plots with higher density. 20-year camphor trees in the present study were still in growth stage, but the growth ceased for trees in higher ages. Both cases demonstrated the classical mass-growth-density relation for individual trees (Vanclay et al. 1995; Niklas et al. 2003). Stronger trend was shown by trees of the permanent sample plots with wider age and density distribution.

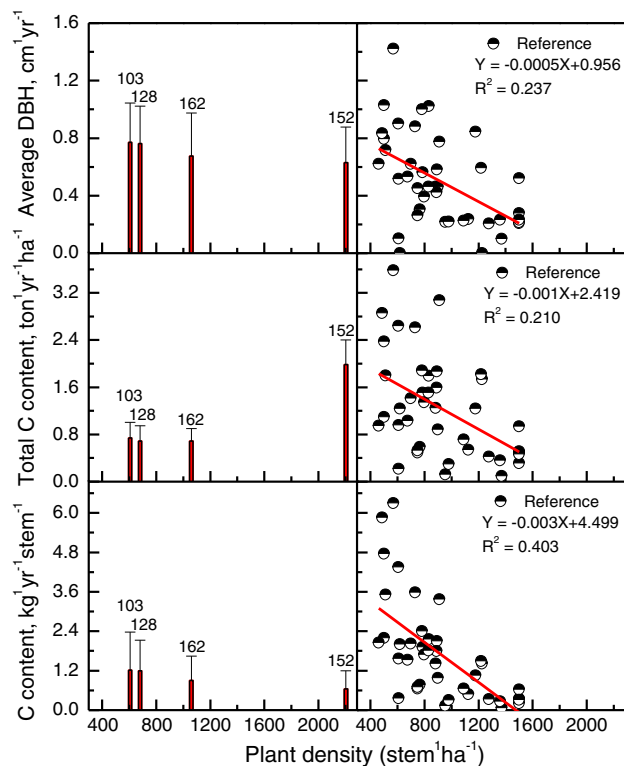


Fig. 4 Annual incremental DBH (*top*), annual total carbon uptake (*middle*) and total C uptake per stem (*bottom*) for camphor trees of the present study (*left panels*) and of the permanent sample plots (*right panels*)

Area-based productivities were shown in mid panels of Fig. 4 in terms of annual carbon sequestered per acre. The above values were 1.98, 0.69 and 0.74 ton C year⁻¹ ha⁻¹ for plots 103, 162 and 152 showed in the mid-left panel of Fig. 4. For the control plot 128, the annual productivity was 0.69 ton C year⁻¹ ha⁻¹. Productivity was increased with increasing plant densities among four plots in the present study. However, increasing plant densities decreased total productivities shown in the mid right panel of Fig. 4. Self thinning phenomena (Niklas et al. 2003) seemed to prevail for the camphor permanent sample plots with longer growth period. There was no clear difference between the productivities in the present study and ones of permanent sample plots. Law of constant yield, total community productivity is independent of plant density (Niklas et al. 2003), seemed prevailed in the permanent sample plots with longer growth period. However, higher densities still led to higher productivity within 20 years of growing period the present study. 11.5 ton C year⁻¹ ha⁻¹ was sequestered by one-year old 16,000 carambola per acre; 4.8 ton C year⁻¹ ha⁻¹ was sequestered by four-year old 3,300 carambola per acre in a subtropical heavy metal polluted site (Li et al. 2009). 3.5 ton C year⁻¹ ha⁻¹ was sequestered by two-year old 13,300 willow per acre

(French et al. 2006). Site difference of heavy metal would make difference: 1–4.2 ton C year⁻¹ ha⁻¹ were sequestered by two-year old assorted temperate hardwoods in different metal polluted sites in UK (French et al. 2006). Values reported in the present study exceeded the reference value for afforestation, 0.5 ton C year⁻¹ ha⁻¹, written in land use, land-use change and forestry (LULUCF) report by IPCC (IPCC 2000).

Individual-based productivities were shown in bottom panels of Fig. 4 in terms of annual carbon sequestered per stem. The above values were 1.22, 0.90 and 0.65 kg C year⁻¹ stem⁻¹ for plots 103, 162 and 152 showed in the bottom-left panel of Fig. 4. For the control plot 128, the annual productivity was 1.19 kg C year⁻¹ stem⁻¹. Productivity per stem was decreased with increasing plant densities among four plots in the present study. The declining trend was more obvious for 40 permanent camphor sample plots showed in the bottom-right panel of Fig. 4. Again, self thinning phenomena (Niklas et al. 2003) seemed to prevail for the camphor permanent sample plots and four plots in the present study. However, higher densities still led to higher productivity within 20 years of growing period the present study. 0.71 kg C year⁻¹ stem⁻¹ was sequestered by 16,000 one-year old carambola per stem; 1.45 ton C year⁻¹ stem⁻¹ was sequestered by 3,300 four-year old carambola per acre in a subtropical heavy metal polluted site (Li et al. 2009). 0.26 kg C year⁻¹ stem⁻¹ was sequestered by 13,300 two-year old willow per stem (French et al. 2006). Site difference of heavy metal would make difference: 0.07–0.31 kg C year⁻¹ stem⁻¹ were sequestered by 13,300 two-year old assorted temperate hardwoods in different metal polluted sites in UK (French et al. 2006). 20-year productivities per stem of camphor tree were not less than very young carambola in very high plant density under sub-tropical climate (Li et al. 2009) as same as the present study. Productivities under sub-tropical climate were higher than ones in temperate climate (French et al. 2006).

Conclusions

Heavy metal accumulation and carbon sequestration of *C. camphora* during 20-year afforestation onto a polluted rice field were analyzed. It was found that the level of differences between soil Cd contents couldn't affect growth of the camphor trees. Leaves, branches and root had significant higher Cd accumulation than sapwood and heartwood had. The above finding suggested the possibility for harvesting leave and branches for phytoremediation, and utilizing the wood for lumbers. Productivities and carbon sequestration capabilities were no less than ones of the reference plots in Taiwan and previous literatures.

Conflict of interest The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Baudouin C, Charveron M, Tarrouse R, Gall Y (2002) Environmental pollutants and skin cancer. *Cell Biol Toxicol* 18:341–348
- Dimitriou I, Aronsson P, Weih M (2006) Stress tolerance of five willow clones after irrigation with different amounts of landfill leachate. *Bioresour Technol* 97:150–157
- Domínguez MT, Marañón T, Murillo JM, Schulin R, Robi BH (2008) Trace element accumulation in woody plants of the Guadiamar Valley, SW Spain: a large-scale phytomanagement case study. *Environ Pollut* 152:50–59
- Drew JT, Flewelling JW (1979) Stand density management: an alternative approach and its application to Douglas-fir plantations. *For Sci* 25:518–532
- French CJ, Dickinson NM, Putwain PD (2006) Woody biomass phytoremediation of contaminated brownfield land. *Environ Pollut* 141:387–395
- Intergovernmental Panel on Climate Change (2000) Land use, land-use change, and forestry: summary for policymakers. A special report of the intergovernmental panel on climate change, at <http://www.ipcc.ch/pub/srl-en.pdf>
- Kabata-Pendias A (2001) Trace elements in the soil and plants. CRC Press, Boca Raton
- Lasat MM, Baker AJM, Kochian LV (1998) Altered Zn compartmentation in the root symplasm and stimulated Zn absorption into the leaf as mechanisms involved in Zn hyperaccumulation in *Thlaspi caerulescens*. *Plant Physiol* 118:875–883
- Lee HT, Feng FL (2010) Investigation of a biomass expansion factor for camphor tree in Taiwan. *Q J For Res* 32:45–54 (In Chinese with English abstract)
- Li JT, Liao B, Dai ZY, Zhu R, Shu WS (2009) Phytoextraction of Cd-contaminated soil by carambola (*Averrhoa carambola*) in field trials. *Chemosphere* 76:1233–1239
- Liu Z, He X, Chen W (2011) Effects of cadmium hyperaccumulation on the concentrations of four trace elements in *Lonicera japonica* Thunb. *Ecotoxicology* 20:698–705
- Maxted AP, Black CR, West HM, Crout NMJ, Mcgrath SP, Young SD (2007) Phytoextraction of cadmium and zinc by *Salix* from soil historically amended with sewage sludge. *Plant Soil* 290:157–172
- McGrath SP (1998) Phytoextraction for soil remediation. In: Brooks RR (ed) *Plants that hyperaccumulate heavy metals: Their role in phytoremediation, microbiology, archaeology, mineral exploration and phytomining*. CAB International, New York, pp 261–288
- McIntyre T (2003) Phytoremediation of heavy metals from soils. *Adv Biochem Eng* 78:98–123
- Meers E, Lamsal S, Vervaeke P, Hopgood M, Lust N, Tack FMG (2005) Availability of heavy metals for uptake by *Salix viminalis* on a moderately contaminated dredged sediment disposal site. *Environ Pollut* 137:354–364
- Mellem JJ, Bajjnath H, Odhav B (2009) Translocation and accumulation of Cr, Hg, As, Pb, Cu and Ni by *Amaranthus dubius* (Amaranthaceae) from contaminated sites. *J Environ Sci Heal A* 44:568–575
- Niklas KJ, Midgley JJ, Enquist BJ (2003) A general model for mass–growth–density relations across tree-dominated communities. *Evol Ecol Res* 5:459–468
- Pilon-Smits E (2005) Phytoremediation. *Annu Rev Plant Biol* 56:15–39
- Probst A, Liu H, Fanjul M, Liao B, Hollande E (2009) Response of *Vicia faba* L. to metal toxicity on mine tailing substrate: geochemical and morphological changes in leaf and root. *Environ Exp Bot* 66:297–308
- Taiwan Forest Bureau (2006) Handbook of silviculture, 2nd edn. Taiwan Forest Bureau, Council of Agriculture, Executive Yuan, Taipei
- Tiwari KK, Dwivedi S, Singh NK, Rai UN, Tripathi RD (2009) Chromium (VI) induced phytotoxicity and oxidative stress in pea (*Pisum sativum* L.): biochemical changes and translocation of essential nutrients. *J Environ Biol* 30:389–394
- Vanclay JK, Skovsgaard JP, Hansen CP (1995) Assessing the quality of permanent sample plot databases for growth modelling in forest plantations. *For Ecol Manage* 71:177–186
- Wang YC (2011) Carbon sequestration and foliar dust retention by woody plants in the greenbelts along two major Taiwan highways. *Annu Appl Biol* 159:244–251
- Yadav R, Arora P, Kumar S, Chaudhury A (2010) Perspectives for genetic engineering of poplars for enhanced phytoremediation abilities. *Ecotoxicology* 19:1574–1588
- Yu XZ, Peng XY, Xing LQ (2010) Effect of temperature on phytoextraction of hexavalent and trivalent chromium by hybrid willows. *Ecotoxicology* 19:61–68