Cost–benefit calculation of phytoremediation technology for heavy-metal-contaminated soil

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HIGHLIGHTS

- A two-year phytoremediation project was introduced.
- Costs and benefits of a phytoremediation project were calculated.
- Costs of phytoremediation project can be offset by benefits in 7 years.

GRAPHICAL ABSTRACT

Cost–Benefit Calculation of phytoremediation project

In less than 7 years, the benefits would offset the costs used for phytoremediation

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ABSTRACT

Heavy-metal pollution of soil is a serious issue worldwide, particularly in China. Soil remediation is one of the most difficult management issues for municipal and state agencies because of its high cost. A two-year phytoremediation project for soil contaminated with arsenic, cadmium, and lead was implemented to determine the essential parameters for soil remediation. Results showed highly efficient heavy metal removal. Costs and benefits of this project were calculated. The total cost of phytoremediation was US\$75,375.2/hm² or US\$37.7/m³, with initial capital and operational costs accounting for 46.02% and 53.98%, respectively. The costs of infrastructures (i.e., roads, bridges, and culverts) and fertilizer were the highest, mainly because of slow economic development and serious contamination. The cost of phytoremediation was lower than the reported values of other remediation technologies. Improving the mechanization level of phytoremediation and accurately predicting or preventing unforeseen situations were suggested for further cost reduction. Considering the loss caused by environmental pollution, the benefits of phytoremediation will offset the project costs in less than seven years.

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1. Introduction

Soil heavy-metal (HM) pollution is one of the main global environmental problems, particularly in China (Hernandez et al., 2003; Li et al., 2015; Toribio and Romana, 2006). Soil HM pollution adversely affects not only the yield and quality of crops, and animal and human

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health, but also the environment (Chen et al., 1999). Soil HM pollution has been paid much attention given that the cleanup costs amount to billions of dollars (Manea et al., 2013; Wu et al., 2014). Cheap and effective technologies would significantly improve the prospects of cleaning-up metal-contaminated sites.

Phytoremediation is considered an economical and environmentally friendly method of exploiting plants to extract contaminants from soil (Padmavathiamma and Li, 2007; Prasad, 2003). This process is relatively cost-effective compared with other remediation techniques. However, a thorough economic analysis for this process is unavailable. Most phytoremediation studies are directed at the biological, biochemical, and agronomic processes (Ali et al., 2013). An economic outlook, instead of simple estimates of the cost advantages of phytoremediation over other techniques, has not been reported.

A method that can effectively allocate remediation funds is necessary because of the high cost of remediation and insufficiency of funds. Decision-making on the application of remediation alternatives is a crucial step after a comprehensive analysis and assessment of contaminants has been conducted (Scholz and Schnabel, 2006). Cost-benefit analysis, using environmental economics, becomes increasingly important (Karachaliou and Kaliampakos, 2011). Numerous methodological studies were conducted to establish models and techniques to calculate cost-effectiveness and aid economic decision analysis (Demougeot-Renard et al., 2004; Lemming et al., 2010; Scholz and Schnabel, 2006). However, available case studies are insufficient, resulting in incomplete essential parameters. Correct decision-making is achieved with enhanced experience and knowledge on the consequences of the decision. These experience and knowledge should be derived from real cases.

A two-year phytoremediation project was performed in the present study. Detailed costs were recorded and analyzed to provide a basic estimate of the real cost of phytoremediation project. The percentage of each item based on the total cost was calculated to determine the unreasonable high costs, facilitating further studies that will reduce phytoremediation costs. In addition, the benefits of remediating farmland soil were tentatively calculated. A few studies have reported the benefit of farmland soil remediation and projected the calculation of the benefits of soil remediation to evaluate the loss caused by environmental pollution (Hao et al., 2004; Vatn et al., 2006; Wu et al., 2004; Zhou et al., 2015). Results of the present study can help determine the most expensive procedure for phytoremediation, favoring subsequent work on reducing costs. In addition, the results can provide the

parameters for future cost-benefit analysis in decision-making for the selection of a remediation technology for contaminated soil.

2. Materials and methods

2.1. Description of the case

Subject area was located in Huanjiang Maonan autonomous county (107°51'–108°43' E, 24°44'–25°33' N), northwest of Guangxi Zhuang Autonomous Region in southwest China (Fig. 1). Huanjiang County is rich in nonferrous mineral resources, and Pb–Zn mines are widely distributed in the area. The tailing dam of the Beishan Pb–Zn mine located upstream of Huanjiang river collapsed in the summer of 2001 because of a catastrophic flood, leading to the spread of mining waste spills on the farmlands along the river (Fu et al., 2015). The cause and status of pollution in the area were quite similar to those of the Guadimar river valley affected by toxic flood (Cabrera et al.).

Approximately 700 ha of soil was seriously contaminated by HM-enriched flooding water. Some regions could no longer sustain agricultural products because of serious pollution, whereas some regions could produce agricultural products but with substandard quality. Local residents manifested some pathological symptoms, such as decreased phosphor in plasma and increased Cd in urine, after digesting crops produced by contaminated soils. HM contamination in this area has become one of the most impressing environmental issues in China.

Soil environmental quality and quality of agricultural products were evaluated before and after remediation. HMs in soils were determined through $\text{HNO}_3\text{--H}_2\text{O}_2$ digestion in accordance with the 3050B method of USEPA (1996). Plant samples were dried, ground, and digested with a mixture of $\text{HNO}_3\text{--HClO}_4$ (Chen et al., 2002b). We performed quality control by simultaneously digesting the samples of certified standard reference materials for soils (GSS-1) and plants (GSV-2) from the China National Standard Materials Center using the experimental samples. The As concentrations were determined using an atomic fluorescence spectrometer (Haiguang AFS-2202, Beijing Kechuang Haiguang Instrumental Co., Ltd., Beijing, China). The concentrations of other HMs were determined using an inductively coupled plasma mass spectrometer (ICP-MS ELAN DRC-e, PerkinElmer, USA).

Over-standard rates were calculated to evaluate the contamination status of the soil in the mining sites. An over-standard rate indicated the percentage of samples with HM concentrations higher than that recommended by China's Environmental Quality Standard for Soils

Fig. 1. Location of Huanjiang County.

(GB15618-1995, Grade II for soil $6.5 \leq \text{pH} < 7.5$: $\text{As} \leq 30 \text{ mg/kg}$; $\text{Pb} \leq 300 \text{ mg/kg}$; $\text{Cd} \leq 0.60 \text{ mg/kg}$) in all of the collected samples. Pollution index was the quotient of the average HM concentration divided by the HM concentrations regulated by China's Environmental Quality Standard for Soils.

Data were analyzed using SPSS version 11.0 (IBM SPSS, Armonk, NY, USA). One-way ANOVA was performed to determine the significance of treatment effects. Multiple comparisons were conducted using the least significant difference method.

2.2. Calculation of costs and methods

Phytoremediation costs were divided into initial capital and operational costs.

Initial capital included pollution investigation, establishment of remediation strategy, soil preparation, construction or purchase of nursery equipment, temporary store, irrigation system, and incineration equipment. Construction of roads, bridges, and culverts was also required to transport the necessary materials.

Operational cost included the cost of labor and materials, cost of using large machines, and the other direct or indirect costs. Cost of labor included labor for seedling, plowing, transplantation, fertilizer application, insect control, irrigation, weed control, harvesting, and some other less significant items. Cost of materials included the purchase of seedling tray, hyperaccumulator seedlings, crop seedlings, farm chemicals, inorganic and organic fertilizer, and some other less significant items. The cost of using large machines included rent for machines during harvest, incineration, and disposal of dangerous waste. The other direct cost included the following: production compensation and rent of land, which were paid to the local farmer; fuel and power cost during the phytoremediation project; construction and environmental supervision, which were paid to a third party. In addition, the HM concentrations of soil and plants were regularly monitored to reflect the effect of phytoremediation during implementation. The indirect cost included the staff wages, administrative expenses, travel expenses, and cost of water and electricity. Phytoremediation is an in situ remediation technology so the unit of cost was in US\$ per square hectometer instead of US\$ per cubic meter, which is normally used for site remediation projects.

Benefit included benefit during and after remediation. Intercropping technology was utilized in the phytoremediation project, which can bring some income during the remediation because of the production of cash crops. After remediation, the soil recovered its function to produce healthy agricultural products and its ecosystem service function, no longer threatening the health of local people. Therefore, the benefit after remediation was calculated by estimating the loss caused by pollution, including the decrease in the quantity of agricultural products, reduced function of ecosystem service, and effect on human health.

Total benefit was calculated as follows:

$$B_{\text{TOTAL}} = B_{\text{DR}} + B_{\text{AR}} \quad (1)$$

where B_{TOTAL} is the total benefit of the phytoremediation, B_{DR} is the benefit during remediation, and B_{AR} is the benefit after remediation.

$$B_{\text{DR}} = P_{\text{SC}} \times Y_{\text{SC}} + P_{\text{MT}} \times Y_{\text{MT}} \quad (2)$$

where P_{SC} and P_{MT} are the values of the cash crop sugar cane and mulberry tree, respectively. Y_{SC} and Y_{MT} are the yields of cash crop sugar cane and mulberry tree, respectively.

$$B_{\text{AR}} = B_{\text{AP}} + B_{\text{EP}} + B_{\text{RC}} \quad (3)$$

where B_{AR} is the benefit after remediation, consisting of the benefit of recovering the function of soil to produce agricultural products that meet the national standards for food (B_{AP}), benefit of recovering soil as a healthy ecosystem component (B_{EP}), and benefit of preventing

human income loss (B_{RC}). B_{EP} and B_{RC} were just-for-once benefit, whereas B_{AP} was an annual benefit.

$$B_{\text{AP}} = \sum P_i \times Y_i \times \Delta A_i \quad (4)$$

where P_i is the price of agricultural product i , Y_i is the yield of agricultural product i , and ΔA_i is the increase in soil area that meet the national standards.

B_{EP} included the benefit of preventing the pollution transfer from soil to water and air, benefit of preventing soil erosion from abandoned soil, and benefit of preventing reduction in biodiversity and some other ecosystem services (Costanza et al., 1998; Su and Jiang, 2008). B_{EP} referred to the reported value of Chinese ecosystem services. B_{RC} was the sum of the benefits of reduced hospitalization cost (B_{HC}) and lowering the decrease in individual income caused by disease or early death (B_{IC}). B_{HC} was directly obtained from the local statistical yearbook.

$$B_{\text{IC}} = W \times N \quad (5)$$

where W is the average personal income in Huanjiang County obtained from the local statistical yearbook, and N is the number of non-farmers who were involved and obtained by a questionnaire survey. B_{IC} only considers non-farmers because B_{AP} already considers the benefit of agricultural production of soil.

3. Results and discussion

3.1. Efficiency of phytoremediation

Soil pollution downstream of the Huanjiang River was extensively investigated. The results showed that the soils downstream were contaminated by HMs (Table 1).

The average concentrations of As and Pb were all higher than the national standards for farmland soil, whereas the average Cd concentrations were lower than the standard. Moreover, 44.1% of the collected soil samples had As concentration higher than the national standard, and 33.3% of the soil samples had Cd concentration higher than the national standard. In addition, 50% of the soil samples had Pb concentration higher than the national standard. Consequently, HM concentrations in a certain amount of agricultural products were higher than the maximum levels of contaminants in foods (Table 2), posing health threat to local residents. The over-standard rates of As, Cd, and Pb in agricultural plants was 13.3%, 26.7%, and 33.3%, respectively.

The remediation plan was formulated according to the investigation results (Fig. 2). Phytoextraction technology (plant hyperaccumulators alone) was adopted for the moderately contaminated soil. Moreover, As and Pb hyperaccumulator *Pteris vittata* (Chen et al., 2002a; Chen et al., 2002b; Ma et al., 2001; Wan et al., 2014) and Cd hyperaccumulator *Sedum alfredii* Hance (Long et al., 2009; Yang et al., 2004) were used in this type of soil. Intercropping system consisting of hyperaccumulators and cash crops with low HM accumulating abilities (Wang et al., 2015) were designed and established on the lowly contaminated soil to give the local farmers some income during remediation. The total area of the remediation project was 19.5 ha, distributed along the Huanjiang River (Fig. 1). The phytoextraction area was 11.1 ha, with

Table 1
Soil environment quality along the Huanjiang river ($n = 191$).

Index	As	Cd	Pb
Concentration (mg/kg^{-1})	36.66 ± 18.6	0.32 ± 0.08	350.5 ± 65.9
Over standard rate (%)	44.1	33.3	50
Pollution index	1.22	1.07	1.4

Over standard rate and pollution index were calculated according to China's Environmental Quality Standard for Soils (GB15618-1995, Grade II).

Table 2
Heavy metal concentrations in agricultural products collected along the Huanjiang River.

Index	As	Cd	Pb
Concentration (mg/kg^{-1})	0.12 ± 0.08	0.17 ± 0.09	0.48 ± 0.25
Over standard rate (%)	13.3	26.7	33.3
Pollution index	0.58	1	1.85

Over standard rate and pollution index were calculated according to the maximum levels of contaminants in foods (GB2762-2012) (As, Cd, and Pb < 0.20 mg/kg^{-1}).

5.6 ha of intercropping of hyperaccumulator and sugar cane and 2.8 ha of intercropping of hyperaccumulator and mulberry tree.

The concentrations of As, Cd and Pb in soil significantly decreased after the two-year remediation project. Available As, Cd, and Pb decreased by 55.3%, 85.8%, and 30.4%, respectively. Cash crop products produced during remediation met the national standards and provided some financial help to local farmers. After remediation, the agricultural products that grew on the soils met the national standards (Table 3).

3.2. Calculation of costs

Costs of the phytoremediation project are summarized in Table 4. Total costs were composed of the initial capital and operational costs, accounting for 46.02% and 53.98% of the total cost, respectively.

Construction of roads, bridges, and culverts constituted the greatest proportion in the initial capital, accounting for 12.67% of the total cost and 27.53% of the initial capital. This result was primarily caused by the local economic development level. Huanjiang is a national poverty county, with very limited funding for infrastructure construction. Some seriously contaminated sites were located in areas with blocked traffic. Considerable amount of funds was used for the construction of roads, bridges and culverts to transport the necessary materials to the contaminated sites. Construction for incineration equipment, irrigation system, and nursery equipment also accounted for high percentages in the initial capital. The preliminary investigation made up to 1.09% of the total cost, similar to several other cases (Day et al., 1997). A thorough preliminary investigation remarkably helps in decreasing the remediation cost (Demougeot-Renard et al., 2004), which was verified in our study. Contamination condition in the project area considerably varied. An appropriate remediation plan can be established only via a thorough survey on the soil environmental quality.

Table 3
Heavy metal concentrations in agricultural products after remediation.

Time	Index	As	Cd	Pb
First year n = 51	Average	0.007	0.0106	0.286
	Median	0	0.005	0.234
Second year n = 46	Average	0.014	0.0067	0.167
	Median	0	0.0048	0.133

Cost of materials, especially the cost of fertilizer, constituted the highest proportion for operational cost, accounting for 19.75% of the total cost and 36.6% of the operational cost. Some areas along the Huanjiang River were not used to produce agricultural products after the flooding in 2001 because of heavy soil pollution, leading to serious lack of nutrient elements. Thus, considerable amounts of fertilizers were applied. Cost of labor also accounted for a high percentage (3.69%) of the total cost. At present, the mechanization level of phytoremediation project remains low because it is still on the initial stage of development. However, the percentage of labor of cost will continue to increase in future phytoremediation projects because cost of labor in China continuously increases (Chen et al., 2013). Therefore, one of the key research directions in our subsequent work is to increase the mechanization level of phytoremediation technology.

3.3. Calculation of benefits

3.3.1. Benefit during remediation

The benefit during remediation mainly comes from the planting of cash crops in the intercropping system, i.e., 5.6 ha of sugar cane and 2.8 ha of mulberry tree. The sale of sugar cane and mulberry tree generated an income of US\$90,932.8 and US\$45,220 during the two-year remediation, respectively. Thus, the corresponding average benefits per hectare of soil were US\$4663.2 and US\$2318.9 (Table 5).

3.3.2. Benefit after remediation

Benefit after the remediation included B_{AP} , B_{EP} and B_{RC} . B_{EP} and B_{RC} were just-for-once benefits, whereas B_{AP} was an annual benefit.

B_{AP} was the average value of the annual output value of land in the last three years, which was obtained from the Statistical Yearbook of Guangxi Autonomous Region. B_{AP} in this region was US\$8241/(ha·year).

Fig. 2. Basic structure of the remediation plan.

Table 4
Costs of Huanjiang phytoremediation project.

Items			Costs (US\$·hm ⁻²)	Percentage (%)
Initial capital	Pollution survey		824.8	1.09
	Establishment of the remediation strategy		824.8	1.09
	Land preparation		577.3	0.77
	Nursery equipment		5893.6	7.82
	Irrigation system		5986.8	7.94
	Roads, bridges, and culverts		9548.4	12.67
	Incineration equipment		7216.5	9.57
	Others		3812.4	5.06
Initial capital in total		34,684.5	46.02	
Operational cost (two years)	Cost of labor	Seedling	164.9	0.22
		Plow	780.8	1.04
		Transplant	206.1	0.27
		Fertilize	123.7	0.16
		Insect control	123.7	0.16
		Irrigation	123.7	0.16
		Weed control	412.4	0.55
		Harvest	185.6	0.25
		Others	657.8	0.87
		Cost of labor in total	2778.7	3.69
	Cost of materials	Seedling tray	82.5	0.11
		Hyperaccumulator seedlings	164.9	0.22
		Crops seedlings	2521.6	3.35
		Farm chemicals	41.2	0.05
		Fertilizer	14,891.9	19.75
		Others	922.7	1.22
		Cost of materials in total	18,624.9	24.71
	Cost to use large machines	Harvest machine	296.9	0.39
		Incineration machine	321.6	0.43
		Disposal of dangerous wastes	206.1	0.27
		Cost to use machines in total	824.8	1.09
	Other direct cost	Production compensation	356.7	0.47
		Rent of land	309.3	0.41
		Fuel and power cost	1948.4	2.58
		Construction supervision	74.2	0.10
		Environment supervision	4011.2	5.32
		Regular monitor	3299	4.38
		Other direct cost in total	9998.8	13.27
	Indirect cost	Staff wage	989.7	1.31
		Administrative expenses	824.8	1.09
		Travel expenses	3888.6	5.16
		Cost of water and electricity	2005.8	2.66
		Others	754.7	1.00
		Indirect cost in total	8463.6	11.23
Operational costs in total		40,690.7	53.98	
Costs in total		75,375.2	100	

B_{EP} was referred to the value of Chinese ecosystem services per unit area of farmland, which was suggested to be US\$959.8/hm² in 2003 (Costanza et al., 1998; Xie et al., 2003), which was US\$1015/hm² in 2014 after multiplying the inflation rate provided by the National Bureau of Statistics of China. B_{RC} was calculated to be US\$11,619.1/hm², using the data from the local Statistical Yearbook and questionnaire survey (Table 5).

The difference between costs and the just-for-once benefits was equal to US\$55,758.9. Inflation rate was hypothesized to be equal to the discount rate. The average benefit of agriculture production was US\$8241/hm². Thus, the benefits would offset the costs used for phytoremediation in less than seven years.

Calculating the benefit of farmland soil remediation is rarely performed. No market value is available for the farmland soil because it cannot be bought or sold. Thus, the value of farm soil could only be indirectly calculated. Several ways originally used to evaluate the loss caused by environmental pollution (Hao et al., 2004; Vatn et al., 2006; Wu et al., 2004; Zhou et al., 2015) were used to calculate the benefit of a soil remediation project. The benefit included the recovery of soil function to produce agricultural products, serve the ecosystem, and decrease human income loss caused by disease or early death. The results show that the ecosystem service function comprised the lowest proportion of only 1/10 of the reduction in human income loss, whereas production of agricultural

products accounted for the highest proportion. Thus, human factor was apparently much more important than the environment in terms of benefits. Whether this attribution of importance is correct is another interesting issue that would be discussed in future studies.

3.4. Comparison with other cases

The costs of the two-year phytoremediation project were calculated and recorded. The cost unit was measured in US\$ per square hectometer, because the remediation is an in situ project. We converted the cost to US\$ cubic meter to facilitate the comparison of the present study to other studies. The soil depth in phytoremediation technology

Table 5
Benefits of Huanjiang phytoremediation project.

Items		US\$·hm ⁻²
Benefits during remediation (B_{DR})	Sugar cane	4663.2
	Mulberry tree	2319.0
Benefits after remediation (B_{AR})	Ecosystem service function (B_{EP})	1015
	Decrease in human income loss (B_{RC})	11,619.1
	Agricultural products producing function per year (B_{AP})	8241.0
		year ⁻¹

B_{DR} , B_{EP} , and B_{RC} were just-for-once benefits, whereas B_{AP} was a yearly benefit.

normally reaches 1–20 cm. Therefore, the cost of phytoremediation of HM-contaminated soil was US\$37.7/m³.

Limited studies have reported on the calculation of the cost and benefit of soil remediation projects, especially for HM-contaminated farmland soil. Most remediation projects were brownfields characterized by organic polluted non-farming sites.

One study on farm soil remediation was found, and the results showed that costs of turnover and attenuation method [(4.7–5.6)/m³] were much lower than solidification [(87–190)/m³], extraction [(240–290)/m³], and plant extraction [(19–78)/m³] (Chen and Chiou, 2008). The turnover and attenuation method mixed the contaminated soil at approximately 30 cm below the surface with the clean or low-contaminated soil in deeper layers to remedy the lands with low HM concentrations. This method was feasible with some areas of contaminated soil. However, this method could not be applied for our projects because the transferred HMs could easily enter into the nearby water system, posing risk to the environment and human health.

Several studies compared the costs of remediation technologies on organic polluted sites. The results showed that the costs of off-site disposal, off-site high-temperature thermal desorption, on-site biopile, and on-site landfarming were (in US\$/m³) 480–813, 81–252, 130–260, and <100, respectively (FRTR, 2007; Inoue and Katayama, 2011). These values were all higher than our phytoremediation project. Another study compared the remediation costs of a gaswork site contaminated by Cu, Zn, Ni, PAH, phenols, cyanide, and BTEX (Day et al., 1997). The costs of soil washing, bioremediation, and excavation were (in US\$/m³) 71.4, 59.9, and 47.8, respectively. These values were also apparently higher than our phytoremediation costs.

Line et al. (1996) evaluated the cost of bioremediation of a hydrocarbon-contaminated site, including preliminary microbiology investigation, site preparation, analytical costs, monitoring cost, supervision cost, etc. The cost was reported to be A\$13.4/m³. In another study, the cost of bioremediation technology was A\$132/m³ (Steinwede, 1995). Remediation costs varied remarkably even though both processes used bioremediation technology in Australia (Day et al., 1997).

Interestingly, bioremediation technology, which has been generally regarded as a cost-effective method, was not the least expensive technology (Chen and Chiou, 2008; Day et al., 1997). This phenomenon is mainly due to the uncertainty of bioremediation technology (Scholz and Schnabel, 2006). The accurate prediction or prevention of the unexpected may be another important research direction in the future other than the improvement of the mechanization level.

The costs calculated in the current study were based on the local rate in China, which may differ from those in other countries. However, despite the old view that the cost in China would be much lower than that in developed countries, recent evidence indicated that the manufacture cost in China continued to increase, which was only 5% lower than that in the US (Sirkin et al., 2011; Tate et al., 2014). Therefore, the values provided in the current study, although not precise, can provide a rough estimation of phytoremediation cost. Comparison of phytoremediation costs in different countries may be an interesting topic which warrants further investigation.

4. Conclusion

A two-year phytoremediation project of soil contaminated with As, Cd, and Pb was conducted. Results show that As, Cd, and Pb concentrations in the soil decreased to levels below the national standards. The total cost of phytoremediation was \$US75,375.2/hm² or US\$37.7/m³, which was lower than those of most technologies reported in literature. Improving the mechanization level of phytoremediation and accurately predicting or preventing the unexpected outcome was suggested for further cost reduction. The benefits of phytoremediation are expected to offset the project costs in less than seven years.

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