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Evaluation of the phytoremediation effect and environmental risk in remediation processes under different cultivation systems

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ABSTRACT

Remediation effectiveness and environmental risks caused by phytoremediation processes under different cultivation systems were assessed at an electronic waste dismantling site. Non-nitrogen-fixing *Eucalyptus globulus* Labill. and nitrogen-fixing *Cicer arietinum* (chickpea) were selected for phytoremediation, while *Eisenia foetida* and *Gus gallus* were chosen as impacted receptors. Chickpea monoculture was least effective for soil remediation, and soil cadmium under this cultivation system had the most potential threats to the environment. The chickpea monoculture cultivation system needs 132 years to reduce the initial soil cadmium concentration to the quality guidelines of China. The environmental risk index of receptors was greater than in other cultivation systems. The greatest remediation effectiveness occurred in the *E. globulus* monoculture with earthworm addition. This approach decreases the decontamination time of cadmium in the soil by 80% compared to chickpea monoculture without earthworms. In addition to a favorable phytoremediation effect, this cultivation system was accompanied by a more acceptable environmental risk index value because *E. globulus* are evergreen trees, unpalatable by livestock, with less litterfall production than chickpeas. *E. globulus* monoculture with an earthworm addition system is especially suitable for remedying cadmium-polluted soil, as it causes the least environmental risk and reduces the time required to decontaminate the cadmium in the soil by 30% compared to the next most effective system. The decision of which cultivation system is more suitable for an anthropogenically influenced site should be balanced between the capacity of the plant to remove pollution and environmental preservation. Data from the present research have provided a new methodology of efficient phytoremediation with relatively low environmental risks.

1. Introduction

Since rapid economic development in developing countries is usually coupled with industrial and mining activities, environmental problems caused by continuous emission of persistent organic pollutants and heavy metals into different media have increased in recent years and have overwhelmed the self-purification capacity of nature (Ullah et al., 2015). Guiyu town, Guangdong Province, south China, is reputed to be the electronic waste (e-waste) capital of the world for its involvement in e-waste dismantling and the recycling business for more than 30 years (Wong et al., 2007). Although uncontrolled open burning and strong acid leaching of e-waste have been banned for many years in Guiyu, soils have been polluted by metals, especially cadmium (Cd).

Heavy metals are not degradable through microbiological or chemical processes (Mahmood et al., 2014). Thus, they generally accumulate in the soil and then leach into groundwater under appropriate conditions. Cd, which is highly toxic, is usually derived from electroplating, plating, fossil fuel consumption, battery discard and tanning (Teixeira et al., 2014).

Due to the adverse effects of Cd, a variety of methods have been developed to treat Cd-polluted soils. Traditional physical and chemical remediation technologies can remediate the contaminated land rapidly but suffer from limitations such as high expenses, change in soil functions, creation of secondary contamination and lack of suitability for treating large accident sites containing moderate pollution (Akcil et al., 2015). Considering

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the negative effects of those methods, phytoremediation is potentially a more ecofriendly technology (Suchkova et al., 2014). Phytoremediation is generally accepted by the public because it has successfully mitigated anthropogenically influenced environments without destroying soil functions (Visoottiviseth et al., 2002). In addition to remedying the polluted soil, phytoremediation provides other benefits, such as soil erosion mitigation, carbon sequestration, biodiversity protection and biofuel production (Hu et al., 2012).

There are still disadvantages of this technology; the main obstacle is disposing of contaminated plants after remediation (Mani et al., 2015; Pandey et al., 2015). Most published studies focus mainly on the ability of plants to accumulate contaminants (Wei et al., 2006) or on the effect of chelate addition to improve phytoextraction (Chen et al., 2003), with rare exploration of the environmental risks caused by phytoremediation. Metals can enter food chains and transfer to other trophic levels through biomagnification during phytoremediation processes, as metal-rich plants can provide pathways for pollutants (Rathod et al., 2014). Hence, although phytoremediation contributes to the mitigation of contaminated soil, the resulting potential risks to the environment must be carefully considered.

Eucalyptus globulus is considered a suitable candidate for contaminated soil phytoremediation, although the Cd content in this species is generally below the thresholds for Cd hyperaccumulators (Arriagada et al., 2007). It performs in line with known Cd hyperaccumulators because its significant biomass production can compensate for low Cd content in plant tissues (Fine et al., 2013). Chickpea and earthworm are well-known nitrogen (N) fixers. Chickpea improves the production of intercropping plants by nitrogen fixing and decontaminates heavy metals from the soil (Huang et al., 2006). Earthworms can increase soil nutrient status via atmospheric nitrogen fixation (Ozawa et al., 2005), and their activity can improve soil conditions by facilitating water and organic matter exchange (Costello and Lamberti, 2009). Forrester et al. (2010) observed that, in direct relation with pollutant translocation, evapotranspiration and water consumption of *Eucalyptus globules* are different under various cultivation systems. Cd can enter the food chain when using edible species such as *Cicer arietinum* (chickpea), *Eisenia foetida* (earthworm) and *Gus gallus* (chicken) for soil remediation, so environmental risk during phytoremediation is a non-negligible factor in the present study. According to the above factors, a series of experiments without chemical reagent addition have been designed in the present study.

The specific objectives of this study were initiated to assess (1) the phytoremediation efficiency of each species under different cultivation systems, (2) the role of nitrogen-fixers in promoting the phytoremediation ability of non-nitrogen-fixing plants, and (3) the potential environmental risks caused by Cd exposure during phytoremediation processes.

2. Materials and methods

A finished ecological geochemistry survey for Guiyu preceding the present experiment showed soil in this town is a typical ferric acrisol, slightly acidic ($pH = 6.4$), having a CEC (cation exchange capacity) of 12.7 cmol kg^{-1} and TOC (total organic carbon) of 42 g kg^{-1}. Heavy metals such as Cd (0.67 mg kg^{-1}), copper (Cu) (56.2 mg kg^{-1}), mercury (Hg) (0.44 mg kg^{-1}), and lead (Pb) (69.5 mg kg^{-1}) in this soil exceed the Chinese soil quality standard II published by the China MEP (2008) (0.3, 50, 0.25 and 50 mg kg^{-1} for Cd, Cu, Hg and Pb, respectively). Only Cd among these elements is further discussed because Cd was a unique element that can be phytoremediated successfully by the chosen species without other additional technology aids in this experiment.

Chaonan, approximately 20 km away from Guiyu, whose major industry is fishing, was chosen as a reference site. This town was never involved in e-waste recycling activity and the heavy metals in its soil have significantly weaker negative impact on creatures (Li et al., 2008).

2.1. Experimental design

In situ experiments were designed to compare the capacity of *E. globulus* with different nitrogen fixers to enhance growth and Cd uptake under different systems (Fig. 1).

The heterogeneity of soil makes it difficult to assess phytoremediation efficiency of planted species for field experiments because the success of phytoremediation is generally determined by point-to-point evaluation instead of averages of a data matrix from experimental sites (Han et al., 2015). To minimize the effect of the heterogeneity of soil on phytoremediation evaluation, a small area with a low heterogeneous soil Cd concentration was selected according to our previous ecological and geochemical survey. Eight contiguous anthropogenically influenced sites (20 m × 24 m) were set up, each divided into six 10 m × 8 m quadrats as replicates, and buffer trees were planted around the perimeter of the quadrats. After large e-waste debris was removed manually, all sites were plowed thoroughly down to the clay basement (approximately 30 cm) and leveled homogeneously by a rotary tiller.

The eight chosen sites were encoded as E1 to E8. E1 to E3 were planting experiments in which earthworms were dislodged and captured by an electrical method (Schmidt, 2001) before *E. globulus* and chickpeas were planted. Three-year-old *E. globulus* with similar characteristics such as tree height (approximately 5.5 m) and diameter at breast height (approximately 8 cm) were cultivated in E1 at a density of 2500 crops per ha in April, 2010. Chickpeas were planted in E2 synchronously at a recommended density of 445,000 crops per ha (Wu et al., 2008). Half of the *E. globulus* and Chickpeas were planted crisscross in E3 instead of as cultivated trees within a row in order to reduce light competition (Forrester et al., 2005). E4, E5 and E6 categories correspond to E1, E2 and E3, respectively, with earthworm application. For the earthworm addition experimental sites, 10 kg of fresh earthworms (Costello and Lamberti, 2009) caught from similar soil conditions were added directly to the center of every quadrat (125 g m^{-2}). E7 was an earthworm control experiment without plants, and E8 was a control experiment without earthworms and plants. Sixty-three 8-month-old free-ranging chickens were divided into 21 equal groups and placed into three of the six quadrats (three chickens per quadrat) of every experimental site (except E8, as there was no food for chickens). A 100-mesh nylon net (200 cm high) was attached to the buffer trees to prevent chickens moving between quadrats. The experimental designs are summarized in Table 1.

E1 is *E. globules* in the monoculture with chicken, E2 is chickpea in the monoculture with chicken, E3 is *E. globules* and chickpea mixed cultivation with chicken, E4 is *E. globules* in the monoculture with chicken and earthworm, E5 is chickpea in the monoculture with chicken and earthworm, E6 is *E. globules* and chickpea mixed cultivation with chicken and earthworm, E7 is the unplanted site with earthworm and chicken and E8 is the bare control.

Each 10 m × 8 m quadrat was further divided into four equal-area sampling sites (5 m × 4 m). Five subsamples of topsoil (20 cm) were collected at each corner and the center of the established sampling site by a stainless steel sampler and then combined into one composite sample. Four collected composite samples for every quadrat were air dried and sieved through a 2.0-mm mesh for analysis.