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Accumulation of Cd in agricultural soil under long-term reclaimed water irrigation

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ABSTRACT

Safety of agricultural irrigation with reclaimed water is of great concern as some potential hazardous compounds like heavy metals may be accumulated in soils over time. Impacts of long-term reclaimed water on soil Cd pollution were evaluated based on the field investigation in two main crop areas in Beijing with long irrigation history and on simulation results of STEM-profile model. Under long-term reclaimed water, Cd content in the top 20 cm soil layer was greatly elevated and was more than 2 times higher than that in the deep soil layer. There was very small differences between the field measured and model simulated Cd content in the plow layer (top 20 cm) and entire soil layer. Long-term model prediction showed that reclaimed water irrigation had a low environmental risk of soil Cd pollution, but the risk would be aggravated when there were high metal loading from other sources. The risk is also depending on the soil and plant properties.

1. Introduction

Facing with severe competition for water resources, increasing attention has been directed to the reuse of reclaimed urban wastewater (Pereira et al., 2011) and irrigation with urban reclaimed water is becoming a common practice in suburban areas of major cities, due to its easy availability, disposal problems and scarcity of fresh water (Biggs and Jiang, 2009). Hamilton et al. (2007) reported that globally, around 20 million ha of land were irrigated with reclaimed wastewater, and the amount would increase markedly during the next few decades as water stress intensifies. Irrigation with reclaimed wastewater has many advantages such as savings in fresh water and fertilizer, reducing pollutant discharges downstream, and so on (Anderson, 2003). However, safety of reuse of such water for agriculture is questioned because some potential hazardous compounds like heavy metals were found to accumulate in soils after long-term irrigation in some studies (Ingwersen and Streck, 2006; Toze, 2006; Lottermoser, 2012).

Many field investigations had been conducted on heavy metal pollution under various reclaimed water irrigation (Pedreto et al., 2010; Singh et al., 2009; Wei et al., 2008; Xu et al., 2010). However, there is no consistency as its impacts were depended on the quality of reclaimed water, irrigation rate, soil properties, crop usage and the irrigation period (Pereira et al., 2012). To promote the safety irrigation with reclaimed water, some questions have to be clarified. Previously, the reclaimed water quality for farmland irrigation was generally poor. For example, in China, most of them were untreated sewage or effluents of primary treatments, and the municipal wastewater and industrial wastewater were not separated in many cases (Yi et al., 2011). As a result, heavy metal pollution problems were broadly noticed in soil irrigated with the reclaimed water (Liu et al., 2005; Xiong et al., 2003). In nowadays, the reclaimed water quality has been greatly improved with the comprehensive wastewater collection and treatment systems. What would happen under improved reclaimed water quality?

As the input from each application is rather small, the accumulation and profile distribution of heavy metal in soils are not always immediately noticeable over short durations. Except for irrigation water, heavy metals may be inadvertently added to cropland soils through application of fertilizers and other amendments as well as atmospheric deposition (Luo et al., 2009). How long would it take to exceed the soil quality standard and what's the role of reclaimed water? In this regard, mathematical models may provide an effective tool to answer above two questions.

So far, model simulation studies on accumulation of heavy metal in soils under long-term reclaimed water irrigation were few. Deng et al. (2008) simulated Cd accumulation in soil irrigated with reclaimed water in Beijing using simplified mathematical equations, assuming reclaimed water for irrigation was the cardinal source of heavy metals in soil and plant harvest was main output. Their prediction results showed that it would need 100 years to exceed the national soil Cd pollution standard of China when irrigated with reclaimed water containing 5 μg Cd L^{-1}. Based on a

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mechanistic model, Chen et al. (2009) studied the distribution of Cd in California croplands under long-term fertilizer application and found that the soil Cd content of the plow layer was doubled after 100 years of normal cropping practices. The model can be used to evaluate the environmental fates of heavy metal in soils with case specific parameters.

To alleviate the water shortage problem, many regions, especially urban centers in northern China, have made a great deal of efforts to maximize benefits of utilizing reclaimed water. About 300 million m^3 reclaimed wastewater was used to irrigate 387,000 ha farmland in Beijing in 2010 (Ma et al., 2010). Around China, it was estimated that about 1000 million m^3 reclaimed wastewater was used for agricultural irrigation in 2010 (Yi et al., 2011). One of the main obstacles hindering reusing more reclaimed water are on heavy metals, which is known to contribute soil heavy metal contamination at some locations in China. While the amount of heavy metals added to soil with one single application is small, concentration of heavy metals in cropland soils may rise over time under long-term reclaimed water. With the long history of reclaimed water irrigation, soils of irrigation areas in Shenyang and Beijing were significantly contaminated with Cd and other heavy metals (Xiong et al., 2003; Yang et al., 2011).

The objective of this research is to evaluate the impacts of long-term reclaimed water on soil heavy metal enrichment by combining field investigation and model simulation of STEM (Soil Trace Element Mass Balance Model) -Profile Distribution. Beijing which leads in the reclaimed water reuse in China was selected as the study area. Cadmium was selected as a case which is easy to accumulate in soil and has the greatest risk of moving into the food chain.

2. Materials and methods

2.1. Soil sampling and analysis

Field investigations were conducted in Tongzhou district and Daxing district, which are two main crop areas in Beijing, China. The study area belongs to a warm-temperate semi-humid zone with continental monsoon climate. The annual precipitation is about 630 mm and the annual mean temperature is 13.1 °C. The typical crop cultivation in the region is rotation of corn and winter wheat.

One typical sample plot was selected in Tongzhou district, which has about 50 year reclaimed water irrigation history from Gaobeidian Wastewater Treatment Plant. Three typical sample plots were selected in Daxing district, which has about 40 year reclaimed water irrigation history from Xiaohongmen Wastewater Treatment Plant. One control plot was selected in Daxing district, which was irrigated with groundwater. Fig. 1 shows the distribution of sample plots.

In each plot, soil profile samples were taken at depth of 0–10, 10–20, 20–30, 30–40, 40–60, 60–80, 80–100, and 100–120 cm. Three replications were conducted and samples at the same depth were completely mixed for analysis. Approximately 1 kg of soil was collected for each depth. After air-drying, an aliquot of each soil sample was ground with a porcelain mortar and pestle to pass a sieve with 100 mesh openings for analyzing soil properties (pH, soil organic matter SOM, total carbon TC, total nitrogen TN) and heavy metals (As, Cd, Cr, Cu, Ni, Pb, Zn). Results showed that there was significant Cd accumulation in top layers in both areas with PLI (pollution level index) greater than 2, while the accumulation of other metals were not pronounced. Therefore, Cd was selected in this study.

Meanwhile, irrigation water samples were collected and its Cd content was analyzed. Table 1 summarizes the information on soil properties of the top 20 cm soil layer and Cd content in the irrigation water.

For the soil Cd concentration analysis, aliquots of 0.25 g finely ground soil were digested using a four acid mixture containing 10 ml HCl, 5 ml HNO_3, 5 ml HF, and 3 ml $HClO_4$. Digested extracts were combined 1:1 with aqua regia and made up to 50 ml with deionized water and further diluted to 250 ml for analyses of Cd using ICP-MS spectroscopy. The detection limit was 0.02 ng L^{-1}.

2.2. Model simulation

The STEM-profile model was used to simulate the fates and transport of Cd in the soil–water–plant system under long-term reclaimed water irrigation. The model conceptually approximates the mechanisms and kinetics of a real field cropland system, by accounting for the interactive processes governing the reactions of trace elements in soils, and the amount removed with crop harvest and leaching out of the soil profile with irrigation water. The model can be downloaded from the website at http://envisci.ucr.edu/faculty/chang.html. Detail information on the model can be found in Chen et al. (2009).

To run the model simulation, parameters on basic information, soil properties, initial conditions, input, boundary fluxes, plant growth and uptake, and root water uptake have to be set. Information from the literature and field investigation was used to obtain these model parameters, and summarized as follow:

(1) Basic information

Based on the field investigation, profile distribution of Cd along the top 120 cm layer over the 50-year period was evaluated by assuming a plow layer depth of 20 cm. The molecular diffusion coefficient for Cd was set to 0.034 $cm^2\ h^{-1}$ and the longitudinal dispersivity was set to 0.2 cm based on Chen et al. (2009). Based on results of lab experiment, adsorption constant of Cd in soil was set to 520 L kg^{-1}.

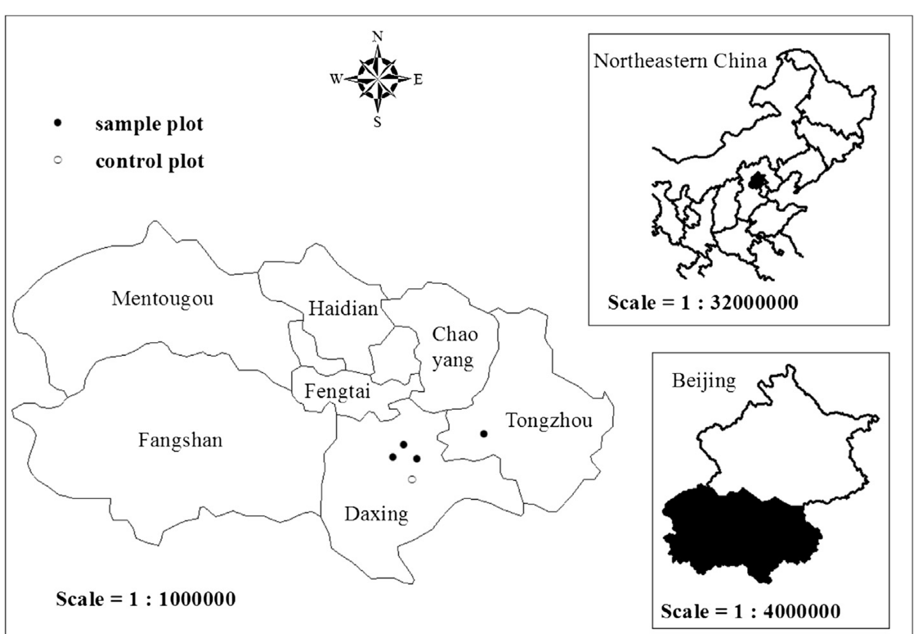

Fig. 1. Location of sample plots.