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Long-term effects of irrigation using water from the river receiving treated industrial wastewater on soil organic carbon fractions and enzyme activities

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ABSTRACT

Reuse of wastewater for agricultural irrigation is one of the useful managements to alleviate the shortage of water resources in arid and semi-arid regions in China. Industrial wastewater from the city of Shijiazhuang is discharged into Wangyang River after treatment. The water is used downstream to irrigate agricultural soils. The objective of this study was to investigate how almost 20 years of irrigation with water from the Wangyang River affected soil characteristics, labile soil organic C and soil enzyme activities, and to compare the microbial response to the long-term irrigation in different locations alongside the river. The results showed that long-term irrigation with river water has resulted in accumulation of Hg, Cd, As, Pb, Cu, Cr, Zn and Mn in the downstream soils. In comparison with groundwater irrigated soils, long-term irrigation with river water significantly increased dissolved organic carbon (DOC), microbial biomass carbon (MBC) and permanganate oxidizable C ($KMnO_4$-C) contents, and dehydrogenase, β-glucosidase, urease, alkaline phosphatase and arylsulphatase activities in the upstream and midstream soils ($P < 0.05$), but not in the downstream soils. On the contrary, the enzyme activities in the downstream soils were significantly decreased after 20 years of river water irrigation ($P < 0.05$). A significant negative correlation ($P < 0.01$) was observed between enzyme activities and concentrations of heavy metals in the soils irrigated with river water, suggesting the inhibition of microbial activity caused by accumulated heavy metals, especially in the downstream soil. The effects of irrigation with water from the wastewater-receiving river on soil quality depends not only on the properties and components of irrigation water, but also on the soil characteristics such as soil type, nutrient conditions and concentrations of heavy metals.

1. Introduction

The shortage of water resources has become an important issue for agriculture of China, especially in arid and semi-arid regions, where the overexploitation of groundwater for agriculture, industry and domestic use led to falling water tables and aggravated the water scarcity. Therefore, a challenge facing agriculture in these regions is to find new resources of water for irrigation. One of the alternatives that have become more common in recent years is reuse of wastewater (Lado and Ben-Hur, 2009; Travis et al., 2010; Morugán-Coronado et al., 2011). Reusing of industry and domestic wastewater for irrigation will not only relieve the pressure on fresh water resources but also takes advantage of the nutrients contained in the wastewater to accelerate the growth of crops, which in turn provides economic benefit for farmers by using less chemical fertilizers (Haruvy et al., 1999; Mekki et al., 2006; Rhee et al., 2011).

However, apart from valuable nutrients and organic materials, wastewater also contains a large amount of contaminants, such as salts, toxic organic components, pathogens, residual drugs, endocrine disruptor compounds and various heavy metals (Alvarez-Bernal et al., 2006; Pedrero et al., 2010), that might accumulate in soils and pose a potential risk to soil quality and productivity in the long term (Friedel et al., 2000). The risk associated with the use of wastewater can be reduced by treating the wastewater before it is applied. Thus, the treated wastewater is recommended for use in agricultural irrigation under controlled conditions to minimize hazards from toxic contaminants of the soils and agricultural products (Al-Lahham et al., 2003).

The effects of treated wastewater irrigation on soil physical, chemical and biological properties have been studied by many investigators (Pedrero et al., 2010; Morugán-Coronado et al., 2011;

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Kayikcioglu, 2012), but most of these studies were based on discharging the treated wastewater into farmland directly. In fact, a large amount of treated wastewater is used for irrigation indirectly by discharging into rivers that supply water for agriculture. Irrigation with water from these rivers may also have impact on soil parameters, such as pH, salinity, cation exchange capacity, buffering capacity, toxic contaminants, and macro- and micronutrients for plant growth (Alvarez-Bernal et al., 2006), thereby affecting soil microbial environment for the crops. Research on the changes of soil quality after long-term irrigation with water from the river receiving treated wastewater is therefore necessary.

The Wangyang River basin is one of the most important wastewater irrigation areas in Hebei Province, China. Farmland soils in this area have been irrigated with water taken from the Wangyang River for more than 20 years. Since there is little natural runoff in this area because of continuing drought, the effluents from wastewater treatment plants are the main water sources of the Wangyang River. Industrial wastewater from its factories in the city of Shijiazhuang is discharged into the Wangyang River following successive biological treatments: anaerobic treatment, hydrolyzation and acidification, primary aerobic treatment and secondary aerobic treatment (Li et al., 2008). However, the treated wastewater also contained considerable contents of nutrients and pollutants. The main parameters (COD and NH_3-N) of the river water exceeded the allowed limit severely (Li et al., 2012), and Cr, Cu, Cd, Pb and Zn were found accumulated in surface sediments of the Wangyang River (Li et al., 2013). Therefore, there is an urgent need to know about the effects of long-term irrigation with water from Wangyang River on soil quality. Compared to physical and chemical characteristics, soil microbiological and biochemical characteristics (e.g. labile organic carbon fractions and enzyme activities) respond more rapidly to changes in soil properties affected by agricultural management practice or pollution, and are thus considered as sensitive indicators to monitor changes in soil (Truu et al., 2008; Chen et al., 2009; Liang et al., 2012). The objectives of this study were: (1) to investigate heavy metal concentrations in soils after long-term irrigation with water taken from Wangyang River; (2) to evaluate the changes of soil quality caused by irrigation using soil biological and biochemical indicators; (3) to compare the microbial response to the long-term irrigation in different locations alongside the Wangyang River.

2. Materials and methods

2.1. Background information of study area

The study area (114°41′–115°09′ E, 37°33′–38°01′ N) was located near the city of Shijiazhuang in Hebei Province, Northern China. This area lies in a semi-arid and warm temperature zone and has a continental climate. Mean annual precipitation is 556 mm, mainly in the period from July to September. Mean annual temperature is 13.1 °C and the frost-free season lasts 200 days. The predominant cropping system is a winter wheat (*Triticum aestivum* L.) – summer maize (*Zea mays* L.) rotation, covering up to 60% of arable land in this area.

The effluents from pharmaceutical, chemical, textile and electronic factories, the major industries that produces up to more than 30 Mm^3 wastewaters $year^{-1}$ in the High-Tec Industrial Development Zone of Shijiazhuang, are discharged to the Wangyang River after secondary (biological) treatment. The mean heavy metal concentrations in the river water were 0.0002 mg L^{-1} for Hg, 0.002 mg L^{-1} for Cd, 0.001 mg L^{-1} for As, 0.026 mg L^{-1} for Pb, 0.069 mg L^{-1} for Cu, 0.030 mg L^{-1} for Cr, 0.075 mg L^{-1} for Zn, and 0.293 mg L^{-1} for Mn according to Zhang et al. (unpublished data). To investigate the basic properties of irrigated water, the river water samples were collected from 5 sites along the river: S1 (upstream), S2–S4 (midstream), and S5 (downstream) (Fig. 1). The water samplings were performed on 23 May, 25 April, 28 May, 28 June and 24 September 2012, respectively. No rain event had taken place in the previous week of the campaign or during sampling days. Selected physical and chemical characteristics of the river water are shown in Table 1. The pH, electrical conductivity (EC) and dissolved oxygen (DO) were measured in situ with a hand-held water quality meter (WTW multi 350i, Weilheim, Germany), while other parameters were determined in the laboratory.

The river water was slightly alkaline (pH 7.16–7.96), and its salinity hazard is considered to be high, since EC varied from 4138 $\mu S\,cm^{-1}$ to 5735 $\mu S\,cm^{-1}$. The chemical oxygen demand (COD) and NH_3-N concentrations exceeded the Chinese recommended limit values (40 mg L^{-1} COD, 2 mg L^{-1} NH_3-N) severely, reflecting a high organic load contained in the river water. In addition, the COD value and nutrient (TP, TN and NH_3-N) concentrations in the river water were much higher in site S5 than those in site S1, indicating a serious deterioration of the downstream water.

2.2. Soil sampling

Soil samples irrigated with river water were collected alongside the Wangyang River after the summer maize harvest in September 2012, since the soil properties were less affected by fertilization in this period, and the data can reflect soil quality for wheat seeding. Triplicate topsoil (0–20 cm) samples were collected from each site (soil S1–S5) with a 10 cm diameter soil core sampler. At each site, the soil was collected from four points randomly and mixed into one sample. In addition, three groundwater irrigated soil samples were collected at Dongzhuang, a village located far from the Wangyang River, which shared similar agricultural management and could be used as control (soil C) (Fig. 1). Field-moist samples were passed through a 2 mm sieve to remove stones and plant materials, and then were divided into two parts. One part was air-dried at room temperature, and ground for physical and chemical analyses. The other part was frozen for biochemical analyses.

2.3. Soil physico-chemical analysis

Soil pH was determined with a Mettler Toledo Seven Easy pH meter by mixing 10 g of soil with 25 mL of 0.01 M $CaCl_2$ solution. Soil EC was determined with a model DDS-307 conductivity meter (REX Instrument Factory, Shanghai, China) by mixing 10 g of soil with 50 mL of distilled water. Soil texture was obtained by the pipette method (Schinner et al., 1996). Soil samples for soil organic C (SOC) measurements were pretreated with 0.5 M HCl to remove carbonates and then ball-milled (Chen et al., 2009). SOC content was determined by dry combustion (Analytik Jena, Germany).

Total concentrations of Cd, Pb, Cu, Cr, Zn and Mn were analyzed by digesting 0.5 g of oven-dried soil samples with 10 mL of HF, 8 mL of HNO_3 and 1 mL of $HClO_4$ as described by Bao (2000). Concentrations of Cd, Pb, Cu, Cr, Zn and Mn in the digestion solution were determined using flame atomic absorption spectrometry (Vario 6, Jena Co. Ltd., Germany). The samples for Hg determination were digested with H_2SO_4–HNO_3–$KMnO_4$ mixture, and those of As were digested with aqua regia (3:1, HCl:HNO_3). Concentrations of Hg and As were determined by an atomic fluorescence spectrometry (AFS-2202, Haiguang Instrumental Co., China). The standard substances (geochemical standard reference sample soil in China, GSS-1) were used to examine the precision and accuracy of determination.

2.4. Soil biological and biochemical analysis

The microbial biomass C (MBC) was determined by the chloroform fumigation–extraction method on fresh soils (Vance et al.,